Modeling recovery of railway system after earthquakes

A dissertation submitted by:

Sergey Kinzhikeyev

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Supervisor:
Dr.- Habil Anita Boros

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Abstract

Railways are one of the largest and critically important infrastructural systems. They play a deterministic role in supporting societal mobility, economy, and state strategic defence. Current earthquake response practice demonstrates that the railway is being better monitored and has a better potential for fast recovery, and as a rule may have less damage compared to other means of transportation. Therefore, railroads can be returned to an operational state quicker. Generally, railways support disaster management quite well, especially in regions where the road systems are less developed.

The overall objective of this thesis is to develop models and methodology for active and adaptive response to earthquake damage to railways. By a more detailed analysis of the overall objective, the following tasks have been identified: (i) study the role of railway systems in disaster response, (ii) analyse the railway damage and the recovery processes, (iii) investigate and develop the required models and (iv) create and test the concept of active and adaptive response management methodology, focused on the fast recovery of railroads in accordance with the operational levels.

The general model of response is a combination of (i) a probabilistic model of railway system damage caused by the earthquake, (ii) a Markov model of damage and recovery, (iii) a probabilistic model of aftershocks, (iv) a statistical model of secondary effects, (v) impact models of management supporting actions and (vi) response process models. The concept validation is based on the simulations. The described response management is recommended to be implemented into the general disaster management procedures.

The major results of the study can be summarized in the following:

- the role of railway systems in the (earthquake) response management should be considerably improved because it is underestimated today. The damage is moderate and can be quickly recovered to the operational level;
- an extensive review of the literature and analysis of the models made it possible to determine the overall indicator of railway damage as a relative unusable length of the track (as a parameter of lost capacity) and to develop a series of models describing the processes of recovery from damage to the railway;
- creation of an active adaptive response to damage of railways by an earthquake based on repeated cycles of zero + six + one steps (Figure-31.), including semi-empirical awareness of the situation - evaluation - decision making between each stage, which is supported by the discussed sub-models using various theoretical, semi-practical calculations and simulations;
- the introduced methodology was applied for modelling and proof-of-concept, including the use of available historical data on railroad damage caused by earthquakes and rapid recovery, using developed sub-models and expert recommendations, suggesting possible solutions in various simulated situations.

The developed methodology will significantly reduce the number of deaths in the earthquake zones since the dynamics of the number of deaths from earthquakes directly depends on the scale and pace of rescue operations.

Key words: earthquake, disaster/emergency management, railway systems, railway damage, response and recovery modelling.
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Introduction

The earthquake is the result of the ongoing billions of years of evolution of the earth's interior and earth's surface. It accompanies humanity throughout the history of its development.

Earthquakes appear stochastically, making it hard to predict them in a short time period. Earthquakes may cause serious problems anywhere in the world, but the hardest shocks take place at the plate boundaries (Figure 1.)

![Worldwide earthquakes (M5+, 1960-2007) and plate boundaries](image)

Figure 1. Worldwide earthquakes (M5+, 1960-2007) and plate boundaries (red [divergent boundaries], blue [transform boundaries], and yellow [convergent boundaries] lines; map generated using [Jones, 2020]).

According to the US National Earthquake Information Centre (NEIC) (Завьялов, 2007), during the XX century, about 2,000 earthquakes with a magnitude of 7 or more occurred in the world. Within 30 years of the end of the XX century, about 1 million people died in them. Earthquakes are ranked as third among all natural disasters by the number of deaths (17% of the total number of the dead). This is due to the significant frequency of their occurrence, catastrophic consequences, the difficulty of their foresight and impossibility of reducing possible scales and consequences.

The transport complex of the countries faces numerous and varied tasks. It supports the mobility of people, the transport of goods, and plays an important role in country defence.

In the event of natural disasters, the volume of transportation may increase dramatically, in order to save the population it is necessary to transport rescue teams and special equipment to the emergency zones, as well as arrange the evacuation of the wounded and sick.

For example: the Ashgabat earthquake (1948), an operation to help the city, in terms of efficiency and organization, can be regarded as a unique example of large-scale rescue operations, which have no analogues in world practice today. The first trains with rescuers, medical teams and food arrived 12 hours later and on the second day after the accident, the railway traffic was completely restored. On October 6, six thousand doctors and medical
workers from other cities arrived at the scene of the tragedy, and on October 9, 6,226 seriously wounded and 8,799 people who lost their homes before October 26 were evacuated (Каррыев Б., 2018).

On the territory of Kazakhstan, a highly seismic region is the city of Almaty, which is the largest metropolis in Kazakhstan. Its population exceeds 1.7 million. In the past, it was twice destroyed by the strongest earthquakes - Vernensky in 1887 with a magnitude of 7.2 and Keminsky in 1911 with a magnitude of 8.2. The analysis of earthquakes in the city of Almaty from 2010 to 2014 showed that their number increased from 90 to 180 earthquakes per year (Михайлова, Соколова, Великанов, & Соколов, 2015).

In the event of an earthquake in Kazakhstan, the bulk of the population, rescue teams and rescue equipment will be transported by rail (Казахстан, 1994), which, in itself, can also be a subject of destruction, thus, suggesting the importance and urgency of solving the problem of the early restoration of railways.

Generally, the role of railways in disaster management can be studied using two different approaches. Traditional rail transport, especially in regions where the road network is less developed, can be used as a strategic element for disaster management (Терёшина, Подсорин, & Данилина, 2017). However, high-speed railways play a pivotal role in a normal economy and life, providing mobility for people. The first approach should be applied to Kazakhstan (Chernyshev, 2014), while for the second approach, Japan demonstrates “best practice” (Suzukia & Li, 2012) (Кобаяши, Мизуно, & Ишибаши, 2012), (Эдвардс, Гудрич, Хелвег, Страус, Эския, & Джрадат, 2015).

Studying the practice and planning of the response and recovery processes (Огura, 2006), (JICA, 2013) can support the development of advanced disaster management systems based on active, adaptive response and recovery. Analysis of the surveillance and damage processes in railway systems caused by the earthquake disasters demonstrate that the railway systems suffer less damage than other means of transportation and they might be returned to the operational state quicker. In several of the disaster events the railway stations had been restored to operation only 6-12 hours after the earthquake’s occurrence. This might be explained by the following three facts: (i) Surveillance of railways systems is more widespread than that of road systems due to their stronger, more complex structural solutions of tracks and bridges built for higher weight vehicles. (ii) The preparedness of railway systems for disaster is higher, partly due to the role of railroads in state defence. (iii) Quicker recovery of the railroads to the operational level because it has more centralised monitoring and operation, and the preparedness including the system of depots with the required materials, tools, machines necessary for quick recovery of the railroads. Therefore, the railway systems – especially in regions where the road systems are less developed – may support the disaster response very well.

The transport disaster damage might be characterised by special indicators like traffic - carrying capacity (Паджетт & DesRoches, 2007). The railway emergency management system deals with the fast restoration of the damaged railways. It includes two processes: emergency response and recovery. Both must be planned and organised in advance in the emergency preparedness process (АДБ, 2010).

There are a lot of articles about dealing with disaster/earthquake response management, while there are only a few models describing the use of railway (Hayashi, Ito, & Ishikawa, 2018) systems and their possible recovery processes.
The first Technical (engineering) goal of the response management is to return the (railway) system to the operational level. In this case, the operational level means that transporting people and goods must be realised. However, some limitations (on speed, weight of wagons, etc.) must be applied and other infrastructure (such as railway stations or signalling systems) may not operate at the originally intended capacity. So, from now on in the paper, the term “response” is used to indicate the start of the response itself and the beginning of a forced recovery process of railroad restoration after an earthquake occurred, which would last for a couple of days maximum. This management step is focused on the technical processes that will result in restarting railroad usage as quickly as possible, even with considerable limitations (for example, speed, maximum loads, etc.).

In accordance with the use of railways in natural disasters, especially for earthquake response, managing the eventual response and recovery of railways becomes one of the most important issues for countries with high speed, high capacity rail systems or railways that play a strategic role in countries with limited road networks.

The overall objective of this thesis is to develop models and methodology for active adaptive response to earthquake damage on railways.

By a more detailed analysis of this overall objective the following tasks have been identified:

i. study the role of railway in disaster response,
ii. analysis of the railway damage and recovery processes,
iii. investigation and developing the required models
iv. create and test the concept of active and adaptive response management methodology.

The developing response and recovery methodology is active, because it is based on

- continuously collecting the objective, measured data,
- situation awareness by use of special indicators, data processing of available information and experts’ contribution,
- analysis by use of a series of sub-models including the damage evaluation, short term modelling the recovery processes, using the Monte Carlo simulation and statistical predictions for aftershocks and secondary effects,
- decisions of objective measurements, evaluations and subjective factors, namely tacit knowledge (practice) of operators, managers.

The response is adaptive, because it is based on recurring cycles of the zero + six + one steps, including semi empirical situation awareness – evaluation – decision making between each step, which is supported by the sub-models employing different theoretical, semi-practical calculations and simulations.

The general model of response is a combination of (i) a probabilistic model of railway system damage caused by earthquake, (ii) a Markov model of damage and recovery, (iii) a probabilistic model of aftershocks, (iv) a statistical model of secondary effects, (v) impact models of management supporting actions and (vi) response process models. The concept validation is based on the simulations. The described response management is recommended to be implemented into the general disaster management procedures.

The thesis contains four major chapters.
The first chapter explores the role of railways in disaster response by using a systematic literature review and preliminary analysis of disaster management methodologies, general regulation of disaster management, earthquake damage and the potential for resilience, damage and recovery processes of rail systems.

The second chapter evaluates and develops possible and required sub-models. After discussing possible simulations, the sub-models will be classified as stochastic rail damage process, probabilistic models for aftershocks, and statistical models designed to predict secondary effects. All these models are described by their mathematical descriptions.

Third major part of the thesis introduces the active, adaptive response and recovery management process. The chapters describe the developed concept for supporting the active, adaptive response management to earthquakes by utilizing the fast recovery of the railway. The proposed general management process is based on recurring cycles of the zero + six + one steps, namely (0) preparedness, (1) collecting and evaluation of data, (2) information about the society and economy, constructions, infrastructures, (3) situation awareness – evaluation – decision process, (4) further and broader evaluation, (5) making a higher-level decision, (6) regular evaluation of reaching the objectives and (7) long term planning. A special simulation methodology is set up to for supporting the managers implementing the recommended response management. Some results demonstrate the applicability of the developed concept.

Finally, the last chapter summarizes results of testing, concept verification and validation of the developed models. Different results and their evaluations will be introduced, including the experts’ opinions on the possible implementation of the concept.

The thesis is closed by the summary of the work done and the definition of new results.

The thesis includes 114 pages, 54 figures and 11 tables. It uses a large number of references, and its methodological results can be applied in learning or adapting models with continuous collection of historical data required for the further improvement of the accuracy of the proposed methodology.
1. Role of railway in disaster response

1.1. Emergency situations – emergency / disaster management

The first rules of emergency management were introduced by military forces in the process of saving towns (from fires). The basic function of the government was to protect the lives and the property of its citizens. Defence of the citizens started by fire fighting. The Roman emperor Augustus was credited with instituting a corps of fire-fighting vigils (“watchmen”) in 24 BC (NAED, 2020). Regulations for checking and preventing fires were developed. In the pre-industrial era, most cities had watchmen who sounded an alarm at the sight of fire. The principal piece of the fire-fighting equipment in ancient Rome and into early modern times was the bucket, passed from hand to hand to deliver water to the fire.

Even today in most countries, about 60 – 75 % of the emergency calls are handled by the fire departments.

In modern history, emergency management, as we call it now, began with growing threats of fire and diseases in large cities and towns. For example, after an extensive fire swept through Portsmouth, New Hampshire, when community and state resources were overwhelmed by the response and recovery effort, the Congress responded with the first legislative action making federal resources available to assist state and local governments (Haddow, Bullock, & Coppola, 2011). This congressional act of 1803 is commonly regarded as the first piece of national disaster legislation in the US. For the last 50 – 70 years, efforts were made to develop response to handle emergencies occurring from unplanned, unwanted events that endanger (i) human life, (ii) material essentials, (iii) cultural values, (iv) nature and living world and /or (v) real estate, which resulted in a system of civil defence initiatives (Rubin, 2007). During this time a series of laws and acts were published (NJSP, 2001) and the developed systems were called emergency management or emergency management technology.

Emergency management deals with emergency evaluation of possible hazards, monitoring / measuring the emergency, evaluation and response on the situation minimizing the losses, recovery of systems to operational level and identifying conclusions required for the reaction, namely preparing them.

The emergency situations are caused by lack of safety. Generally, the goal of safety sciences is the human life protection (Rohacs, 1988). Nowadays, it is quite a complex problem, due to:

- the accelerated use of finite natural resources,
- rapid industrialization,
- wide use of dangerous goods and technology,
- a lack of knowledge in application of new scientific and technological results,
- the known climate change,
- globalization in economy, political and social interrelationships.

Emergency management (Haddow, Bullock, & Coppola, 2011), (Rohacs, 2004) is a set of instruments, technologies, methods and procedures applied to protect human life and property. This is a process of reducing the loss of lives and property and protecting assets from all types of hazards through a comprehensive, risk-based, emergency management program of mitigation, preparedness, response, and recovery. The theory and methodology development of emergency management were improved after the September eleven terror action (McEntire, The Status of Emergency Management Theory: Issues, Barriers, and Recommendations for Improved Scholarship, 2004).

In short, emergency management is the minimization of risks and losses associated with the emergency situations. It has a multi-agent and multi-phase nature. It may use several indicators,
or indexes like the City Disaster Exposure Index (CDEI), that is a ratio of initial population of the city at risk and the initial population of the city (Endrissi & Askari, 2019). The success of recovery management depends on the delays and the optimal use of available financial support. The cost of recovery might be estimated well (Endrissi & Askari, 2019), while the delay prediction is a rather complex task.

Emergency management has two different classes depending on the size of emergency situations. One of them deals with local emergencies of small size, like serious accidents, involving dangerous freight during transportation and such. The other class of emergency situations contains natural or industrial disasters (or those caused by military actions) affecting large territories and large numbers of people, important cultural assets, or large parts of nature. This class includes earthquakes, floods, industrial catastrophes (Chernobyl, Bhopal), large terror actions (Sept. 11.) and some epidemics.

Nowadays, emergency management is based on the actions shown in Figure 2. This is an extended, so-called active system containing brief information about the tasks and requirements in order to make high-level solutions.

![Figure 2. System and tasks of emergency management (extended active system) (Rohacs, 2004)](image-url)
This thesis deals with the response and recovery of the railway systems after an earthquake, partially addressing preparedness for such situations. The term “disaster” would be used to describe large-scale emergency situations. Disaster management is a set of management tools and techniques applicable to preparedness, disaster monitoring/warning, response and recovery, as well as the studying of the events for collection of the experiences, risk analysis and mitigation. One of the best practices of disaster management is demonstrated by American FEMA – (FEMA, 2020) and especially according to the rail damage caused by earthquakes – Japan (JCO, 2019), (FDMA, 2020). The advanced disaster management may use the system engineering (Ed. by Badiru & Racz, 2014) and the well-structured command and control system C4ISR – (Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance) published first by US Department of Defence (DOD, 1997). In Europe, the emergency management is coordinated by a dedicated centre, Emergency Response Coordination Centre (ERCC, 2020). Nowadays, C4ISR is a totally integrated, active and adaptive management systems developed by the army and is going to support all the large technical and technogenic systems. Figure 3 shows the concept applied by Huawei in developing future system management. This system has at least three serious novelties comparing to the “classic” C4ISR:

- collaboration, including the collaboration of the different services/ministrations and collaboration of national and international services,
- instead of regular computing, cloud computing is used for data processing/data management,
- using new ICT (information communication technology) concept based on Internet of Things, namely integration of widely distributed sensors and actuators into a single system through Internet connections,
- introduced new command structure.

![Figure 3. C-C4ISR stands for Collaborative & Command & Control, Communications, Cloud, Intelligence, Surveillance and Reconnaissance as foreseen by Huawei (Goulding, 2020)](image)

Integrating the IoT into the command system opens very large windows for possible improvements of the preparedness, condition monitoring, and awareness and for quicker response. Figure 4 shows a wheel of enabling technologies for Internet of Things of railways.
The last novelty, the command structure means, the system must be controlled by a hierarchy of strategic, tactic and operation managements.

The use of IoT and new command structure allows developing new active, adaptive disaster response management.

As it was said, this thesis deals with disaster response, that might be defined as a command and control System (Wang, Chen, Xu, & Qu, 2018). Of course, the response is always in close connection and interdependence with recovery (McEntire, 2014). The response starts before the disaster occurrence and includes the short – term and even partly the intermediate recoveries namely first couple of days up to about 3 – 5 weeks (FEMA, 2011).

This paper states that the response uses the capabilities necessary to save lives, protect property and the environment, and meet basic human needs after a disaster occurrence. (FEMA, 2011). From the technological point of view, the response returns the required systems (in this case railway transport) to the operational level at first. Such Ability to adapt to changing conditions, withstand and rapidly recover from disruption caused by emergencies is called resilience (FEMA, 2011).

The response management, here, deals with controlling the usage of available resources. The control must be defined by using a continuously repeated situation awareness – evaluation – decision-making process. This type of control is active because the management, being a part of the total system, actively makes decisions depending on the situation awareness. The decision must always to be adapted to the changing situations (Djalante, Holley, & Thomalla,
2011). The terms and methods of active and adaptive controls are used more, for example to building structural dynamics (Bitaraf, Hurlebaus, & Barroso, 2012).

1.2. Regulation of the disaster management

The disaster management systems must be coherent with regulations. The national regulations developed by Kazakhstan as well as international regulations were analysed in detail.

The required preparedness level is (i) expected by the economy and people (stakeholders), (ii) estimated by professional experts and (iii) defined by policy and rule-makers. The preparedness level should make a balance between the demands of the economy and society and available financial support, between the acceptable risk and willingness to pay for decreasing the hazards.

The laws, directives, rules, and requirements regulating disaster management were investigated. The top-level emergency management is defined by policymakers (Sylves, 2019) and by legislation. There are many international and national laws defined to support emergency management.

Comparison of international regulations (IFRC, 2014), (IFRC & UNDP, 2015) shows that the national regulations usually follow the concept described by the CMDA (The Caribbean Disaster Emergency Management Agency) (CMDA, 2013). The further analysis of the emergency management regulations of the US, Japan, European, Hungarian and Kazakhstan regulatory systems had resulted in three major conclusions:

- There are no principal differences in the compared regulatory systems, in neither their structure nor their contents.
- There is a lack of regulation related to the use of railway systems in disaster management.
- Kazakhstan is better prepared for possible utilization of the railway system in disaster response.

Reasons of the last conclusion might be explained (I.Makarov, 2015) by the
- geographical position of Kazakhstan: plate boundaries in the regions where earthquakes appear very often,
- fact that, in some regions of the country, the road systems are poorly developed, making usage of the railway system more frequent.

Traditionally, due to the strategic role of the railway system in defence, the railroads in Kazakhstan are well prepared for quick recovery in case of disasters.

Each country organizes its central national response framework according to laws (Kinzhikeyev, 2020), (Tóth, 2000), (Boros & Robotka, 2019). The U.S. may have the largest and most regulated framework (FEMA, 2020) (FEMA, 2008). In Europe, the Civil Protection Mechanism (EU, Decision No 1313/2013/EU of the European Parliament and of the Council on a Union Civil Protection Mechanism, 2013) regulates the cooperation between the EU Member States and 6 Participating States in the field of civil protection, with a view of prevention, improving preparedness and response to disasters. Through the Mechanism, the European Commission plays a key role in coordinating the response to disasters in Europe and other parts of the world and contributes to at least 75% of the transport and/or operational costs of deployments. The EU uses the latest results of scientific research and available emerging technologies. For example, a special service (Copernicus Emergency Management Service) that provides maps of disasters based on satellite information (EU, 2020) is established. The EU also supports several important scientific projects, such as the H2020 Espresso project.
(Enhancing Synergies for disaster Prevention in the European Union) (H2020, 2016 - 2018) which is publishing many scientific papers on the topic.

In the field of civil protection, all countries have a general law that operates at the national level, which includes the principles of physical protection of people and goods in cases of risk, guidelines for preparedness, for example, training courses, rehearsals of evacuation plans, etc. (Responses in emergency situations (Bank Asian Development, 2010)). In the case of Spain, Korea and Japan, specific laws exist regarding a particular type of risk. For example, Japan has 21 hazardous laws, such as the Special Measures for Large-scale Earthquakes Act (Tadashi Okamoto, 2016). Moreover, in some cases, laws reach a level of detail that represents content structures for emergency plans such as France, Spain, and the United States (European Commission European Civil Protection and Humanitarian Aid Operations, 2017).

In the Spanish Rail Sector Act of 2003, the Railway Infrastructure Administration (ADIF) must define a contingency plan at the national level to determine the measures that should be taken in the event of a railway emergency. ADIF takes into account coordination with railway operators (especially with RENFE) and with national emergency services. This plan, which should be updated every 2 years, must be approved by the Ministry of Public Works (Administrador de Infraestructuras Ferroviarias, 2016).

In Germany, the General Railways Act (Allgemeines Eisenbahngesetz) requires railway infrastructure administrations and railway companies to build and operate safely, prevent risks, participate in emergencies and investigate incidents when they occur (Massimo Florio, 2017). To this end, the Deutsche Bahn Infrastructure Administrator (DB) defines contingency plans that include guidelines, roles, and coordination protocols to consider in case of an emergency. DB develops these plans on its own, however, emergency services or the Bundeslender (states) are taken into account in developing such plans.

The Government of Japan does not establish requirements for the railway authorities to define an emergency plan if they ensure the safe operation of the railway. However, the JR Group does identify guidelines that contain a set of rules to be followed in the event of a railway accident. Since these manuals are not requested by the law, they do not need to be approved by any governmental body, and the frequency of their updating is also not specified (JR East Group, 2017).

The following Table 1. summarises the railway emergency plans developed in the reference countries, the parties responsible for their development and approval, the periodicity and the related regulation.

Table 1. Definition of Parties involved in emergency plans (source: Railway organizations websites and interviews)

<table>
<thead>
<tr>
<th>Country</th>
<th>Regulatory environment</th>
<th>Railway entities</th>
<th>Other entities</th>
<th>Validity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Infrastructure manager (railway, stations)</td>
<td>Railway operators</td>
<td>Federal/ Regional government</td>
</tr>
<tr>
<td>France</td>
<td>Order of August 12, 2008 Decree №. 2006-1279 on National Railway Safety (Ministry Transport) defines the content and update requirements Intervention and Security Plans</td>
<td>RFF collaborates in emergency plan definition</td>
<td>SNCF defines emergency plans at prefecture level (Main agent)</td>
<td>Prefectures collaborate in emergency plan definition</td>
</tr>
</tbody>
</table>
### Germany
- Civil Defence Act of 1997 civil defence law delegates emergency planning and operational preparation in peace time entirely to the Lander and their structures.
- **DB AG**
  - Defines emergency plan *(Main agent)*
- Bundesländer collaborates with DB in definition, procedures, responsibilities
- Not available

### Spain
- **ADIF** defines emergency plan *(Main agent)*
- **RENFE** collaborates
- Not available
- 2 years

### Japan
- Railway business Act. Secures the safety of transportation and ensure a sound advancement of the railway business.
- Japan Railways Four companies (East, West, North South Railways) collaborate in the emergency plan *(Main agent)*
- Not fixed, updated only if necessary

### Korea
- Railway Safety act 2004 defined by Ministry of Transport (MLTM), states that a comprehensive safety plan shall be defined every 5 years and annually implemented.
- Does not participate
- Safety plan implementation
- The MLTM defines the Railway safety Plan *(Main agent)*
- 5 years
- 1 year implementation updating

### USA
- 49 code of Federal Regulations 239 sets up the obligation to Railway players of adopting and implementing an EMS.
- **AMTRAK** defines emergency plan *(Main agent)*
- Federal Railway Administration -Department of Transportation
- Not available

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In addition, design and construction norms and standards were revised and updated to reflect the real seismic hazard and to more correctly determine the seismic loads acting on buildings and structures (in particular, a new map of seismic zoning with corresponding peak ground accelerations, an altered form of design earthquake spectra, a new system of acceptable damage factors, soil condition factors, etc.) were introduced.

However, these laws also diffused government responsibility for natural disasters, responding to emergencies among multiple agencies. Some roles were clearly defined and others were not, which has created some confusion and duplication of efforts (CESDRR, 2018).
The concept of transport security in the Russian Federation (Семенов, 2018) is based on the principle of acceptable risks. A whole series of legislative acts and regulatory documents have been directed towards the implementation of such an approach to ensure railway safety in the Russian Federation.


The development of measures to improve the railway safety system is also envisaged by the Russian Railways Development Strategy until 2030 (Минтранс, 2008).


The legislation of the Republic of Kazakhstan in the field of natural and man-made emergency situations is based on the Constitution of the Republic of Kazakhstan, as well as on other regulatory legal acts (Adilet, 2014).

The legislative framework in the field of prevention and liquidation of emergency situations of natural and man-made nature of the Republic of Kazakhstan is summarized in Figure 5 and 6.

Currently, in the Republic of Kazakhstan, legislation in the field of natural and man-made emergencies, including issues of ensuring seismic safety, is at the stage of formation of the foundations and their specifications at the by-law level.

State regulation of public relations in this area is based on:

- Constitution of the Republic of Kazakhstan;
- constitutional laws and decrees of the President of the Republic of Kazakhstan, having the force of constitutional law;
- industry laws;
- governing specific issues in the field of emergency;
- Decrees of the President of the Republic of Kazakhstan governing the order and forms of state administration by higher, central and local executive bodies;
- other codes, laws and other legislative acts;
- special by-laws and regulations.
Figure 5. The Structure of legislation support of disaster management in Kazakhstan (КЧС, 2017)

- decisions of local representative and executive bodies;
- special by-laws of recommendations of an interdepartmental nature;
- relevant acts of an interdepartmental nature (to regulate relevant internal issues in the field of emergency situations);
- SNiP and instructions on various issues;
The Plan of preparedness of Kazakhstan for natural disasters should be important in resolving issues in the field of emergency shown in Table 2. (Петров, 2017).

Table 2. Plan of preparedness of Kazakhstan for natural disasters (Че-ник, 2019)

<table>
<thead>
<tr>
<th>No</th>
<th>Events</th>
<th>Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Organization of emergency rescue operations in the emergency zones of rescue, evacuation of people, animals and property</td>
<td>rescue, evacuation of people, animals and property</td>
</tr>
<tr>
<td>2.</td>
<td>Organization of the deployment of the Operational headquarters and the operation of the hotline telephone; deployment of the Operational headquarters</td>
<td>deployment of the operational headquarters</td>
</tr>
<tr>
<td>3.</td>
<td>Organization of medical and psychological assistance to the victims and the affected population</td>
<td>medical and psychological assistance to the affected population</td>
</tr>
<tr>
<td>4.</td>
<td>Conducting rescue and emergency operations in the emergency zone</td>
<td>emergency rescue and emergency work</td>
</tr>
<tr>
<td>5.</td>
<td>The organization of sanitary-epidemic and sanitary-preventive measures in the emergency zones associated with infectious and parasitic diseases, localization and elimination of foci of infectious, parasitic diseases, poisoning among the population</td>
<td>localization and elimination of foci of infectious, parasitic diseases, poisoning among the population</td>
</tr>
<tr>
<td>6.</td>
<td>Ensuring the transportation of the affected population by rail, air, river and road transport; delivery of the affected population to safe areas</td>
<td>delivery of the affected population to safe areas</td>
</tr>
<tr>
<td>7.</td>
<td>Carrying out measures to prevent and reduce damage from accidents at chemical, radiation and fire hazardous facilities, as well as in reservoirs and dams, preventive measures at hazardous facilities</td>
<td>preventive measures at hazardous facilities</td>
</tr>
<tr>
<td>8.</td>
<td>Relocation of emergency rescue services and units, as well as other forces involved in the emergency zone for emergency rescue and urgent work</td>
<td>relocation to the emergency zone</td>
</tr>
</tbody>
</table>

The plan regulates, based on current legislation, the mandatory and recommendatory actions of state bodies and organizations, regardless of their forms of ownership, public associations and the population in the field of providing comprehensive preparation for natural disasters and responding to them in cases of their threat or occurrence.

The modern legislation of the Republic of Kazakhstan in the field of emergency is characterized by:
- duplication, inconsistency, subjectivity and declarative nature of certain norms;
- inconsistency with international law.

These shortcomings practically do not allow the full usage of the legislation as the main management tool in the field of emergency situations, and therefore ineffective administrative-command forms of management prevail in this area, which entails excessive material and moral costs.

In the framework of the project of the Government of the Republic of Kazakhstan and UNDP "Building the capacity of Kazakhstan's preparedness for emergency situations" - KAZ /
01/002 (05.2001 - 05.2002), the Committee on Emergency Situations of the Republic of Kazakhstan developed the proposal "Codification of the legislation of the Republic of Kazakhstan in the field of emergency situations and civil defence." The aim of the project is to analyse the current legislation in the field of emergency situations and develop an appropriate Code, which should significantly improve the quality of the legal framework in the field of emergency situations.

Disaster management can be defined as the organization and management of resources and responsibilities to address all humanitarian aspects of emergencies, in particular, this is the process of how we “prepare for, respond to and learn from the consequences of major failures” (Elliott, 2014).

In the case of railways, disaster management provides quick, orderly, effective and adequate disaster relief measures. The term “disaster management” was first used on Indian Railways in 1986 and has been popular since then (Srinivas P., 2018).

As previously indicated, there are 2 types of hazards that can cause an emergency: natural (or geophysical) hazards and technological hazards (Ляшко В.Г., 2015).

No country, community or person is protected from the effects of disasters. Disasters, however, can be and have been answered for, responded to, recovered from, and have their consequences mitigated to a certain degree (Ibrahim Lone & Subramani, 2016).

As disasters tend to be recurring events, disaster management forms a cycle (Yu, Yang, & Li, 2018).

The traditional process of disaster management compose of two stages: pre-disaster risk-reduction and post-disaster recovery stage. The first consists of activities such as prevention, mitigation and preparedness while the second includes the activities of response, recovery and rehabilitation (Nojavan, Salehi, & B., 2018).

The mitigation is different to the other phases of "Disaster management cycle" in that it focuses on long-term strategies for reducing the risks associated with future disasters (Pathirage, Seneviratne, Amaratunga, & Haigh, 2015).

Mitigation can be sub-divided into non-structural and structural measures. Structural measures refer to engineering solutions for mitigating potential disaster impacts while non-structural measures can include organizational activities such as land-use and legislative acts (UNDRR, 2016).

Based on the foregoing, it can be concluded that mitigation - those actions that can be taken before a disaster to minimize losses - is based on a long-term commitment to reduce the vulnerability of rail transport to all natural disasters. Effective mitigation destroys the belief that little can be done to avoid disasters.(FEMA., 2015).

In the Republic of Kazakhstan, public administration in the field of protecting the population and territories from natural disasters, including earthquakes, accidents and catastrophes and emergency situations caused by them, is carried out within the framework of the State system for the prevention and liquidation of natural and man-made emergencies, which was created in accordance with the formation of the Cabinet of Ministers of the Kazakh SSR of June 25, 1991 No. 935.

The State Emergency Service acts on the basis of legislative acts of the Republic of Kazakhstan and the Government Decree “On the State System for the Prevention and Liquidation of Emergencies” dated August 28, 1997 No. 1298, as well as other regulatory legal acts (Figure. 6).
Figure 6. The structure of the state system of warning and emergency response in Kazakhstan
The State Emergency Service is designed to prevent and eliminate natural and man-made emergencies.

The structure of the State Emergency Service includes:

- The Committee on Emergency Situations of the Ministry of Internal Affairs of the Republic of Kazakhstan, carrying out general management of the State Emergency Service, its territorial and subordinate organizations;
- Governing bodies, daily management bodies (duty dispatch services) of central executive authorities and republican organizations designed to prevent and liquidate emergencies;
- Full-time emergency rescue units of central and local executive bodies and organizations, territorial and object formations, and civil defence for emergency situations;
- Forest protection services, disaster medicine service, unified aviation search and rescue service, environmental monitoring and control services by potentially dangerous objects of central executive bodies and organizations, the Republican system of seismological observations and earthquake prediction.

### 1.3. Earthquake damage and response

Earthquake is an unexpected violent shaking of the ground initiated by sudden release of energy in the Earth's lithosphere that creates seismic waves (Ischuk, 2018), (Stein & Wysession, 2005). Earthquakes cause great destruction in nature and built environment. It is often followed by volcanic actions, tsunami, landslide, changes in ground level, and / or flooding, dam breaks. The earthquakes may injure and kill large amounts of people because of increase of population and urbanisation. The deadliest earthquake ever recorded occurred at Shaanxi, China, in 1556. Collapse of cave dwellings carved into bluffs of soft glacial loess killed 830 000 people (Stein & Wysession, 2005). It is a fact, the 100 key earthquake with highest losses and damages occurred in XX century (that is about 1 % of the total damaging earthquakes) caused 93 % of fatalities globally (Daniell, Schaefer, & Wenzel, 2017).

The earthquake statistics demonstrates that the earthquakes are appearing at the plate boundaries (Braile, 2009). Some countries are located in such dangerous regions. For instance, according to the Ministry of Emergencies of the Republic of Kazakhstan, earthquakes occupy first place among potentially dangerous natural disasters for Kazakhstan (Figure 7, 8.). About 6 million Kazakhs and about 500 thousand square kilometres of the republic’s area are exposed to this danger. These facts indicate the importance of ongoing research in Kazakhstan on mitigating the effects of possible seismic disasters (Нурмагамбетов А., 2012). As it can be identified, with a magnitude of 8.2 (Нурмагамбетова А., 1999), in addition, over the city, in the mountains of Almaty there are about 40 moraine lakes that can cause floods and mudflows, which will also lead to deaths (Fig. 8., 9.) (Committee on Emergency Situations Ministry of Internal Affairs of the Republic of Kazakhstan, 2016), also, within the city, 11 chemically hazardous objects (Fig. 10.).

There are many different statistical and probabilistic models for long–term predictions of earthquakes, while the short –term prediction is rather problematic (Helmstetter, Kagan, & Jackson, 2006). On the other hand, the seismic wave and rupture propagation are studied on very high levels (Bray, Seed, Cluff, & Seed, 1996) (Hori, 2018), (Wesnousky, 2006). There are good models, but there are still a lot of uncertainties, depending on the structure of soil, its real features.

Damage and losses caused by an earthquake can be estimated by using different approaches, from semi empirical formulas up to high level complex statistical, dynamic or stochastic methods, finite element methods calibrated by experimental data, etc. (McGuire, 2004), (Erdik, Şeşetyan, Demircioğlu, Hancilar, & Zülfikar), (FEMA, 2017), (Guo, Gao, & Hu, 2020).
The seismic hazard of the city of Almaty is associated with the seismic-generating zones of the Northern Tien Shan. The seismic potential of the zone is quite large - the possible magnitudes of the strongest earthquakes with foci in these zones are from 7.5 to 8.5, respectively, and the intensity of tremors in the city can reach from 8 to 10 points. The strike of the zones coincides with the strike of the Zailiysky and Kungey Alatau ridges, the Chiliko-Keminsky fault zone (Fig.11) (Mikhailova N.N.; Sokolova I.N.; Velikanov A.Y.; Sokolov A.N., 2015).
Figure 9. Mudflow hazard map of the Big Almaty Lake (Чс-ник.kz, 2020)

Figure 10. Map of risks of exposure to emergencies in the Almaty region (ЧС-ник.KZ, 2019)

Figure 11. Number of earthquakes in Almaty (Mikhailova, N.N.; Sokolova, I.N.; Velikanov, A.Y.; Sokolov, A.N., 2015) (Kinzhikeyev, S.; Restas A., 2019)
The types of natural and man-made hazards in the Almaty region have been identified (Table 3.)

Table 3. Catalog of natural and man-made emergencies in Almaty

<table>
<thead>
<tr>
<th>№</th>
<th>Name of emergency</th>
<th>Emergency characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Earthquakes</td>
<td>The city of Almaty is located in the transition zone from the ascending northern slope of the Zailiysky Alatau ridge, on the stretch of the cones of the Bolshaya and Malaya Almatinka rivers and the adjacent descending Ili depression. Meanwhile, the current level of seismic intensity from weak earthquakes in the city area remains very high. Every year, within a radius of 80 km from the city of Almaty, 200 weak earthquakes occur. According to the current map of seismic zoning of Kazakhstan, the city of Almaty is located in a 9-point zone. Within the city limits, zones of tectonic disturbances have been identified, 5 tectonic faults crossing the city territory occurring at a depth of up to 1200 m, covering almost the entire territory of the city. According to the Institute of Seismology, 70% of multi-story residential and administrative buildings and 50% of industrial facilities were surveyed in the city for seismic resistance. Private buildings of the city remained unexplored. As a result of an earthquake with an intensity of 9 points in the city According to forecast estimates, Almaty will have the following situation: Total losses among the population will 350 thousand people dead. Energy, gas and water supply systems, sewer networks will be practically disabled.</td>
</tr>
<tr>
<td>2.</td>
<td>Floods</td>
<td>Spring floods and floods in the city of Almaty occur as a result of overflow of the channels of the Bolshaya and Malaya Almatinka rivers, the Esentai river, small the rivers Bedelbai, Batareika, Butakovka and others due to the abundant melting of snow in the mountains Zailiysky Alatau, associated with a sharp increase in air temperature in the spring-summer period and heavy rainfall. Most likely flooding of the areas of the city takes place from May to July. With GU &quot;Kazselezhshchitoy&quot; observed the state of wastewater and dams. During floods lower parts of cities, towns, highways get submerged, also damaging industrial and transport facilities, etc.</td>
</tr>
<tr>
<td>3.</td>
<td>Mudflows</td>
<td>In the city of Almaty, mudflow is possible along river beds Big and Small Almaty, which have high mudflow activity. In the event of catastrophic mudflow and destruction dams in the place of the watershed on the Malaya Almatinka river mudflows descend along the Esentai riverbed. With catastrophic mudflow and exceeding, permissible water flow along the rivers Big Almaty - 30 cubic meters. m / s, Malaya Almatinka - 5 cubic meters m / s the total flooding area of Almaty will be 38.8 sq km. The main source of catastrophic mudflows on the rivers Bolshaya and Malaya Almatinka in 70 - 75% of cases are heavy rains, 20-25% - a breakthrough of moraine-glacial lakes and in 5% - a breakthrough of temporary reservoirs formed as a result of earthquakes. According to preliminary estimates, 6919 people may be in the mudflow zone, of which 4891 people could be helped and 2028 people are at a high risk. Activities for the implementation of the city anti-mudflow complex Almaty are a practical solution to the complex problem of protecting a large industrial and cultural centre from the destructive effects of mudflows.</td>
</tr>
<tr>
<td>4.</td>
<td>Snow avalanches</td>
<td>The mountains of Zailiysky Alatau, in the foothills of which the city of Almaty is located, is exposed to avalanche hazard. An avalanche is a mass of snow falling or sliding off steep mountainsides, similar to a collapse. The speed of avalanche is, on average, 20-30 m / s. The fall of an avalanche is accompanied by the formation of an air pre-flood wave, from which the greatest damage occurs. Snow avalanches form on slopes with a steepness of more than 25 ° with a snow cover height of more than 30 cm. An avalanche dangerous for human life can form on a slope with a height of only 10 m. The volumes of large avalanches reach 1 million m, the speed is 100 km / h, the impact force is 100 t / m, track length - several kilometres. The avalanches are caused by heavy snowfalls, when during the day the height of snow exceeds 20 cm, thaws and snowstorms. Avalanches are most common during snowfalls.</td>
</tr>
</tbody>
</table>
but the largest avalanches usually occur during spring thaws. Snow avalanches damage mining enterprises, industries, block roads and railways, destroy power lines, destroy forests, interfere with normal the work of tourist facilities. On top of all it also is a cause of many deaths.

5. Landslides

Landslide hazard in the low mountain zone has significantly increased in recent years. They occur in Zailiysky Alatau and in the suburbs of Almaty due to the heavy usage of territory for the construction of cottages, also causing numerous accidents on water lines. In the foothill zone of the city of Almaty, potentially dangerous areas are Kensai massif and Koktobe mountains, areas of the Kamensky plateau, summer cottage “Wide gap”, natural boundary Butakovka, sanatorium "Remizovka", MKR. Kokkaynar St. Sarlybay Nasyra, rooms are at the registration, MKR. Bai Besik St. Beysebaeva, numbers find at registration, Pyatiletki district Ul. Shatsky St. Bakhtarminskaya. The largest and most dangerous is the landslide section of the Kok-Tobe Mountain on the southern border of the city.

6. Epizootic, infectious, exotic and parasitic diseases from animals. 

Epiphytota

In Almaty, the following infectious and parasitic animal diseases can spread: brucellosis, tuberculosis, smallpox, rabies, Crimean, haemorrhagic fever, foot and mouth disease, anthrax, leptospirosis, emphysematous carbuncle, leukaemia, pasteurellosis, echinococcosis.

The source of infections, as a rule, are sick farm animals that, bypassing veterinary posts, are imported from dysfunctional neighbouring areas.

In the territory of Almaty region there are:

- 13 natural foci of plague; 182 points permanently dysfunctional for anthrax, also on the list of dangerous infections: typhoid fever, acute intestinal infections, viral hepatitis.

7. Technological danger

The hazardous industrial facilities of the city include:

- 222 gas stations with a total volume of 222200 cubic / m;
- 18 tank farms with a total volume of 180,895 cubic meters;
- 11 enterprises with potent toxic substances (28.7 tons of ammonia) (Fig.7);
- 20 hydraulic structures, of which sel-retaining-6;
- 6 enterprises - for the production of alcoholic products using a combustible substance - alcohol.

1.4. Damage and recovery of railways

Transport systems have deterministic roles in the economy and further developments (Banister & Berechman, 2000), (Rohacs, 2005). According to European statistics (EC, 2017), out of all freight transported nowadays, road transport has nearly a 50% contribution, while water-based is approximately 30% and the rail is a little over 11%. The several earthquake events have demonstrated that railway transport is a critical infrastructural system. Its faster recovery to the operational level plays the most important role in saving and evacuation of people and goods from the dangerous zones as well as supporting the recovery to normal life and economy (Каррыев, 2017) (Suzukia & Li, 2012). The paper comparing the United States and Japan earthquake preparedness and response (Greer, 2012) starts the emergency support functions with the transport. As it defined, transport must be coordinated by the designated department and in order to increase safety level, movement restrictions should be introduced as well as coordination with telecommunication and information industry. The response management may use many different models from simplified semi-empirical up to high-level simulations and calculations (Chang S. E., 2003) (Berkoune, Renaud, Rekik, & Ruiz, 2012), (Chang, Peng, Quyang, Elnashai, & Spencer, 2012).

Development of a number of road transport sectors can be significantly limited due to difficult climatic conditions and low bearing capacity of soils, which do not allow the construction of roads for vehicles with high axial load, and in some cases also paved roads (Черепанов, Бодосова, Моисеева, Хоменко, & Казанцев, 2012).

The above factors state that in some countries, rail transport represents the main part of a single transport system and it is the most important integrating component (Fig. 12.), in connection
with which rail transport acquires the role of the main trunk transport, while the rest of the types (except for pipelines) are assigned the role of auxiliary (Tereshina, Podsorin, & Danilina, 2017).

Figure 12. The proportion of individual modes of transport in the total freight turnover (Макаров & Макаров, 2015).

Rail transport takes a leading position in the transport system of most countries of the world. Railway transport, which carries out huge volumes of passenger and cargo transportation, including dangerous and especially dangerous ones, belongs to the branches of the national economy with an increased risk of emergencies (ИПЕМ, 2019).

In Kazakhstan, with its vast territory and natural features, rail transportation is the basis of the transport system. As of January 1, 2018, the railway transport network of Kazakhstan consists of 16.061 thousand km of railways (Кноема, 2018).

A general distinction can be made between two different types of disasters that can cause an emergency, namely natural (or geophysical) and technological (Шарипханов, Раимбеков, & Кусаинов, 2015) (earthquakes, landslides, tsunamis, volcanic activity); climatological (extreme temperatures, drought, forest fires); hydrological (avalanches, floods); meteorological (cyclones, storms) and biological (epidemics of diseases, insect/animal plague).

Technological hazards are defined as hazards created by humans and artificial technologies, but they can be caused by the geophysical process and natural hazards. For example, floods and earthquakes can release hazardous materials into the environment, causing secondary technological or natural emergencies (Ляшко В.Г., 2015). Those that are caused directly by deliberate or unintentional human actions are referred to as anthropogenic technological hazards: (i) hazardous materials (mutagens, carcinogens); (ii) artificial environment (structural accident, fire); (iii) transport (automobile, rail, sea, aviation accidents); (iv) wapons of mass destruction (nuclear, chemical and biological devices, explosives, aviation) and (v) sociological (war, terrorism).

By rapid safety technology development in period of years 1960 – 1990, the number of disaster, that occurred yearly, had been reduced by 8 times (Fig. 13.).
According to the Committee on Statistics of the Republic of Kazakhstan, from 2010 to 2016, 973 technological disasters occurred on the railways of Kazakhstan, 497 people died and 516 were injured (Fig.14.) (Комстат МНЭ РК, 2018).

The main reasons for railway accidents are:
(i) derailments of transport from rails,
(ii) collision with another vehicle or obstacle (any major obstacle on the railway track),
(iii) explosions / fires on board during the transport of dangerous goods and
(iv) "human factor" - errors and violations of the rules of operation.

Based on the data on the number of deaths and injuries caused by accidents on the railway, we can conclude that 80% of people suffered from technological disasters in the southern region of Kazakhstan. This is due to the population density and urbanization of this region.

However, to date, there is no data on the forecast of possible victims of natural disasters, in particular earthquakes and floods in the Southern region.

Analysis of technological catastrophe data on the railway and using the QGIS software, the number of dead and wounded in the regions of Kazakhstan is shown (Figure 15.).
The railways systems as large critical structural systems that are contributing an important part of general transportation system and they play deterministic role in supporting the society mobility, economy and state strategic defence. The railway systems (Pyrgidis, 2018) are the sets of engineering (as trains, tracks), civil engineering (bridges, tunnels, stations) and management (monitoring and controls) elements.

The railway has some unique characteristics comparing to the road transport. For example, according to the Japan freight rail (JR Freight) (Railway, 2020) the rail has higher efficiency (28 freight wagon are equivalent to 65 10-ton trucks and the rail is a well-scheduled transport without traffic jams. The emission polluted by the train is about 11 times less than emission of the trucks providing the same transport unit.

The railway can be destroyed as a result of earthquakes. A survey of damage to railroad components during past earthquakes shows damage to bridges, embankment failures, vertical and horizontal track misalignments, tunnel misalignments, failure of tunnel linings, structural damage to railroad buildings, and overturned rail cars and locomotives (Table 4.) (Kislov K.V.; Gravirov V.V., 2017).

Table 4. Historical data on the destruction of railway transport during earthquakes

<table>
<thead>
<tr>
<th>Affected area</th>
<th>Year</th>
<th>Magnitude</th>
<th>Comments</th>
<th>Photo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kern County, USA</td>
<td>1952</td>
<td>7.5</td>
<td>Extreme tunnel damage to 30 miles (50 km)</td>
<td><img src="image1.jpg" alt="Photo" /></td>
</tr>
<tr>
<td>Alaska, USA</td>
<td>1964</td>
<td>9.2</td>
<td>Track and bridge damage up to 150 miles (240 km)</td>
<td><img src="image2.jpg" alt="Photo" /></td>
</tr>
<tr>
<td>Location</td>
<td>Year</td>
<td>Magnitude</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>---------------------------</td>
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<td>----------------------------------------------------------------------------------------------------------------------------------------------</td>
<td></td>
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<tr>
<td>Seattle, Washington, USA</td>
<td>1965</td>
<td>6.5</td>
<td>Damage to the Union Pacific Railway occurred when hillside fill slid away from beneath a 121-m section of the branch line just outside Olympia more than 60 km from the epicentre</td>
<td></td>
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<tr>
<td>Guatemala</td>
<td>1976</td>
<td>7.5</td>
<td>The photo is looking north along railroad tracks that were twisted and offset 107 cm by the Motagua fault, which is perpendicular to the tracks</td>
<td></td>
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<tr>
<td>Kobe, Japan</td>
<td>1995</td>
<td>6.9</td>
<td>Extensive track and bridge damage to 45 km</td>
<td></td>
</tr>
<tr>
<td>Hector Mine, USA</td>
<td>1999</td>
<td>7.4</td>
<td>Bridge and track damage to 15 miles (10 km), signal damage to 25 miles (40km)</td>
<td></td>
</tr>
<tr>
<td>Chi-Chi, Taiwan</td>
<td>1999</td>
<td>7.7</td>
<td>Track damage from liquefaction to 55 km</td>
<td></td>
</tr>
<tr>
<td>Kocaeli, Turkey</td>
<td>1999</td>
<td>7.8</td>
<td>Minor tunnel damage up to 90 km</td>
<td></td>
</tr>
</tbody>
</table>
These damages caused by earthquakes seems very hard. However, the recovery of the railway to the operation level might be performed during a short time. For example in the summer of 1962 on the Ashgabat railway (the railway section of Kazandzhik, Nebit-Dag), a piece of railroad was destroyed by mudflows and floods in some places with a length of about 42 kilometres separate pickets, the railway track lattice was severely deformed and carried by the flow 150-170 meters from the axis of the track. The restoration involved forces and means of transport, the local population and military units of the Moscow Region (4 battalions of motorized rifle and tank regiments with tractors and engineering equipment). The work carried out around the clock. The first passenger train through the restored section was allowed to pass 28 hours after the start of recovery, and the freight train after 36 hours. Recovery carried out for three and a half days.

Another important specific aspect associates with organization and implementation of railway transportation in the aftermath of the earthquake in Armenia. At December 7, 1988 earthquake was unexpected for not only the population of Armenia, but also for government bodies, institutions and forces designed to organize and conduct rescue and other urgent work. The situation on the railway transport was extremely difficult. As a result of the destruction and damage of railway facilities transport was interrupted by train traffic on the railway section with a length of 110 km. In the earthquake area, 67 people were killed and 75 railroad workers were injured, 947 families were left homeless.

To assess the consequences of the disaster and take operational measures to restore the movement of trains, an operational group was created in the Transcaucasian Railway Administration and at the train stations Kirovakan and Spitak.
The work of railway transport was complicated (Елисеев, 2001):

- untimely unloading of wagons, due to their unplanned arrival;
- lack of mechanization for loading and unloading;
- the arrival of other goods not intended for priority restoration work;
- in addition, the volume of traffic on the North Caucasus and Azerbaijan railways exceeded the railway capacity, as a result of which the daily number of idle trains on these railway lines during December-January was at least 180-200, and therefore locomotive brigades and locomotives from other railways were involved in providing the required volumes of rail;
- an increase in the volume of traffic in difficult transport conditions caused a sharp increase in the volume of information received, processed and transmitted by transport authorities, including reports on the progress of restoration of train traffic, planned works, attraction of additional forces and means, etc.

The following critical objects can be identified from the experience of restoration work on railway transport after natural disasters: bridges, tunnels, railway track, station, depot, electric substation, automation, telemechanic and communication system is summarized in Figure 16.

Figure 16. The railway system and its major (critical) elements

The analysis of the available information on railway system damages caused by earthquakes is summarised in Figure 17. As it can be seen, there is only limited information about the damage to the individual elements of the railways systems.
Figure 17. The maximum distance from the epicentre to the railway facilities that were damaged (drawn by using data from (William & Byers, 2004), (Шекербеков, Разрушение транспортных сооружений при сильных землетрясениях прошлого с 1895-1988 годы, 2010))

Figure 17. demonstrates, the size of damage zones (maximum distance from epicentre), which may considerably vary (see the track damages).

Major critical elements are the track and bridges. Damages of these critical elements are analogue to damages of the road infrastructures. However, practice shows that the railway system can return to its working level (with possible limitations, as speed limits) within 4 – 6 hours and complete after 8-12 hours (Bryant, 2000) (Каррыев Б., 2018).

The specialists identify the bridges as most critical elements of railway systems (Misra & Padgett, 2017), because their recovery is a more complex task than repairing the tracks. Therefore, preliminary actions should focus on bridges. Several possible solutions that require attention:

i. improving the rules and requirements for design, construction, and operation;
ii. developing passive and active monitoring systems including establishing remote condition monitoring;
iii. developing the preparedness level and;
iv. introducing active total management of the recovery process.

Here passive monitoring means that several sensors might be integrated into the bridge structure, video cameras can be established in the environment, etc. The information can be collected through the internet remotely. Active monitoring can be classified into light and heavy methods. Light methods deals with sensors activating after earthquake occurrence, such as sending drones to explore and estimate the damage levels. Active monitoring uses sensors and small actuators for initiating testing signals (like impact or vibration) in construction elements and recording the resulting response signals. The test might be activated automatically (regularly) and from the distance from command points (for example in case an earthquake event occurred).

The role of rail, especially the fast train transportation is increasing rapidly. Therefore, the preparedness and preliminary actions for reducing the earthquakes are very important tasks. Japan has a system predicting the possibility of earthquakes damaging as the detectable P waves caused by the occurred earthquakes move with a 40 – 60 thousand times lower speed than electric signals. Due to the usage of the system, the P-wave alarm was issued 3 seconds after the occurrence of the great East Japanese Earthquake, on March 11, 2011 (Edwards, Goodric, Hellweg, Strauss, Eskijan, & Jaradat, 2015). The P-wave sensor cut the power to trains and the
emergency brakes decelerated the Shinkansen train travelling through the Sendai area at a speed of 270 km/h. Within 70 seconds, after the large vibration occurred the train’s speed was decreased by 100 k m/h only. After another 30 second, the P-waves that reached the train, which was moving at a speed of 4.4 km from starting the break, completely halted the train. The rapid reaction prevented derailment (Edwards, Goodric, Hellweg, Strauss, Eskijan, & Jaradat, 2015).

27 Shinkansen trains were moving, when the earthquake occurred. Nevertheless, due to the early warning system no high-speed train derailed. That day the Tohoku Shinkansen had in total 1200 damage sites, including 540 damages to electric poles, 470 broken overhead lines, 10 damages to bridge bearings, 2 damages to tracks in tunnels, etc.

The restoration including observation, investigation, permanent repair works, running test of Shinkansen cars was performed quickly. About 4 % of the line were restored within one day, more than 25 % - within 4 days. The Shinkansen was totally restored during the period of 49 days including the aftershock occurring on April 7, 2011, which caused serious seismic damage of the railroad again (Kobayashi, Mizumo, & Ishibashi, 2012).

During the Great East Japan Earthquake the Sendai oil refinery, the only refinery located in the Tohoku region, was badly damaged and stopped working, leaving the Tohoku region without fuel. However, a high-capacity freight railway quickly responded to this situation (Suzukia & Li, 2012).

Studying the practice, planning the response and recovery processes (Ogura, 2006), (JICA, 2013) may support developing the advanced disaster management system based on the active, adaptive response and recovery.

The railroad system is vulnerable to earthquakes in much the same way as the roadway system is. The survey of damage to railroad components caused by earthquakes resulted to the identification of damage to bridges, embankment failures, vertical and horizontal track misalignments, tunnel misalignments, failure of tunnel linings, structural damage to railroad buildings, and overturned rail cars and locomotives (Consortia, 2000). In wider approach, the railway system might be more important in countries with less road infrastructure (like Kazakhstan) and its (railroad) better preparedness for disaster management.

During this study three important features of the railway systems were identified:

i. The railway system is a large net with many distributed elements controlled by the centralised management. It uses the same monitoring and controlling elements;

ii. It is well prepared for disaster management, because of its strategic role in the country’s economy and defence;

iii. It has well developed, centralised monitoring and managing system that is operated by a hierarchically and territorially distributed subsystems (usually based at railway stations).

This thesis uses approach shown in Figure 2. to the railway systems. It introduces only the modelling the damage and recovery processes of the railroads after earthquakes for supporting the emergency management in active implementation of the railroads to disaster response management.
2. Evaluation and development of the sub-models

2.1. Possible modelling

The analysis of the railway system damage and recovery processes in disaster management demonstrates that the processes are typically stochastic, dynamic, active endogenous systems managed by the use of subjective decision processes.

Here stochastic means that the disasters caused by earthquakes, aftershocks and secondary effects (such as floods, tsunami) appear in unpredictable, random ways and the actual situation depends on the characteristics of soil and geographic area. In addition, local parameters and environmental conditions (such as weather situations, air temperature, etc.) introduce rather large uncertainties. As the processes applied after earthquakes to recover the system to operational level are developed on the basis of situation awareness, analysis and decision making of the system are controlled actively. The control originates from the operators that seem to manage the system from outside, but in reality, they are the elements of the systems. Therefore, such system is called as endogenous.

The decision on emergency management methods, applied for the quick recovery of the system to operation, is made by humans. Human operators make decision on subjective ways, by utilising their knowledge and practice. There is a reason why these need high level of support. By taking into account these considerations, the railway system damage – recovery process might be described by using the following general model:

\[ \dot{x} = f(x, p, z, u, t) + \sigma(x, p, z, u, t)dW, \]  

(1)

Where \( x \) is a state vector defining the state of railway destroyed and recovery processes, \( p \) is the parameter vector containing the parameters of the soil, geographic and railroads, \( z \) is the vector of environmental characteristics, \( u \) is the control vector, \( W \) is the Wiener noise vector and \( \sigma \) is the noise transfer matrix. Here \( z \) can be changed randomly and \( p \) parameter vector contains uncertainties.

The system of equation (1) can be reduced by introducing a unique state variable or state index that is determined by using several state variables.

Figure 18. describes and explains the simplified process (1). The \( x \) is assumed by \( x_u \) usability (percent of usability or percent of operability) of the railway system. The damage caused by earthquake reduces the usability considerably (for 20 – 30 %). Response increases the usability to 80 – 90 %, meaning the system can be operated safely with some possible limitations. Response goes for about 1 – 2 weeks. During the transition phase (about 1 week), the railroad systems will be prepared for more detailed repapering. After that, the real recovery process is
applied for the return of the system to the conventional operation. That may take from 3 – 5 weeks up to a few years (Liu, Shi, & WQang, 2017).

A simple variable percent of unusable railroads $l_{\text{ut}}$ is recommended to use as a state variable to evaluate and manage the damage and recovery of the railway in response to earthquakes. It can be called the relative unusable railroad length. The unusable means that it cannot be used as the line or part of the track. For instance, the lengths of unusable track sections due to a destroyed bridge can be calculated as a length of a given track from starting the roundabout to returning to the track.

There are three important assumptions defined to the relative unusable railroad length:
- the total railroad length is calculated as the total length of track potentially applicable in disaster response;
- the relative unusable railroad length might change from 0 to 100 %;
- this range might be divided into equal-distance sub-ranges, while the regions cannot be divided in linear way (see Figure 9.).

![Figure 19. Division of possible space of relative unusable track length](image)

In Figure 19. the curves start at high levels due to the damage caused by earthquakes. The responses reduce the relative unusable track length, while the aftershocks increase the $l_{\text{ut}}$ suddenly by steps. The aftershocks are appearing in a random way.

Another important comment: the control vector has legal and physical control elements, specifically the regulation requirements on the design and building of safe railroads, railway systems as well as methods of monitoring, continuous maintenance and repairing, rebuilding the objects like tunnels, bridges, tracks.

Finally, to further simplify the model, the random disturbances might be cancelled, because the general functions (first part of equation (1) on the right hand) might be used as a statistical dynamic equation (by using average values of vector elements).

By using these assumptions, the equation (1) might be rewritten in a simpler form:

$$\dot{x} = f(x, p, z, u, t).$$

By taking into account the completion of the space of changes in relative unusable track length, $l_{\text{ut}}$ can be represented as

$$l_{\text{ut}}(t) = \sum_{i=1}^{n} p_i(t) l_{\text{ut}_i},$$

where $P_i$ is the probability of the relative unusable track length parameter, $l_{\text{ut}}$ at time $t$ is in the $i$-th sub-space, and $l_{\text{ut}_i} = \left(l_{\text{ut}_i} - l_{\text{ut}_{i-1}}\right)/2$ for $i = 1, 2, \ldots n$. 

40
This way, Equation (2) can be reduced to modelling the changes in a probability vector \( \mathbf{P} \). Assuming (i) the state of the railway is in the relative unusable track length parameter in \( i \)-th subspace depicted as the \( i \)-th state, \( S_i \) can be approximated by an exponential distribution process, (ii) the time of changing from one state to any other \( (S_i \rightarrow S_j) \) is nearly zero and (iii) the process must always be in one of the states, the changes in probability might be defined by the transition probability density

\[
\lim_{\Delta t \to 0} \frac{\mathbb{P}[S_{t+1} = j | S_t = i]}{\Delta t} = \beta_{i,j} \quad i, j \in \{1, n\}. 
\]  

(4)

By using the probability transition matrix, \( \mathbf{\beta} \), the probability vector \( \mathbf{P} \) can be calculated from the following matrix equation:

\[
\dot{\mathbf{P}}(t) = \mathbf{P}(t) \mathbf{\beta}(t). 
\]  

(5)

This equation approximates the stochastic process of continuous space and time, by a well-known stochastic process, the Markov process of discretised space and continuous time. As a result, Equation (5) can be rewritten into the discretised form:

\[
\mathbf{P}(k+1) = \mathbf{P}(k) + \mathbf{\beta}(k)\mathbf{P}(k). 
\]  

(6)

The analysis of Equations (2) – (6) results in the conclusion: all the important effects governing the damage-recovery process (equation (1)) can be characterised by defining the transition matrix \( \mathbf{\beta} \).

The time interval \( k \) can be chosen as \( \Delta t = 0.05 \) or \( \Delta t = 0.1 \) hour. This interval is small enough to model the damage – recovery process and large enough to approximate the earthquakes as simple impulse events and its effect on the relative unusable track length, \( l_{ut} \), might be modelled as a step function.

In addition to the relative unusable track length, \( l_{ut} \) defined by Equation (3), several other indicators can also be defined. For example, the relative population, the relative number of people \( N_p \) that cannot access \( (N_a) \) and use the railway systems from the total population \( N_t \); \( N_p = N_a / N_t \). In this case, equations similar to (3) – (6) can be applied.

The introduced model (5), (6) is a very simplified, first order model. At least the following four comments and possible ways of improvements can be emphasized.

- The model is a stationary with transition matrix \( \mathbf{\beta} \), estimation of its elements, \( \beta_{i,j} \), need more accurate information, which is limited by the available historical data. Aftermath of this problem can be moderated by re-estimating the elements of the transition matrix during the recurrent simulation and prediction cycles.
- The assumption that spending time in \( i \)-th subspace in space of relative unusable track length of railroads before changing from state \( S_i \) to \( S_j \) can be approximated by an exponential distribution seems not correct. It would be better to use real distribution, resulting to implementation of the semi Markov approximation. However, there is a lack of information about the real distributions of times being in given sub-spaces. It can be assumed that the time, \( \tau_{i,j} \), is in different sub-space during transition \( S_i \rightarrow S_j \) in space of indicator, so \( l_{ut} \), can be defined using the normal distribution. Actually, that is completely mathematically correct, but, the transition matrix elements can be defined as

\[
\beta_{i,j} = 1/\bar{\tau}_{i,j}, 
\]  

(7)
meaning that, as a first order approximation average time determining from the normal distribution can be applied too. Other possible way is to use average or weighted average of transition time from state $S_i$ to $S_j$.

- The model can be applied to different recovery processes. For example, in case of investigation of the operability of the railway station in a city damaged by earthquake it is fully applicable. The freight and passengers flow can be implemented at rather destroyed railway stations, too. However, the recovery of the rail track, can be operated after repairing it for at least the level at which the rail vehicles can be moved through the damaged section in any limited way (like with reduced, or limited speeds). On the other hand, in case of a high-speed rail, the track must be fully repaired and tested before starting its operation. These aspects must be taken into account during simulation and analysis.

- The full railway network cannot be simulated by using simple Markov approximation of the operation, because of the possible use of shortcuts.

The general damage – recovery process of the railway systems caused by earthquakes is composed of several sub-processes requiring sub-models.

2.2. Probabilistic model of railway system damage caused by earthquakes

The first sub-model is used for the first order prediction of the size of damage of railway systems during earthquakes in the form of relative unusable track length, $l_{ut}$. It is based on the available models of the appearance and propagation of seismic waves, ruptures and available data on damages of railway systems:

$$l_{ut}(t) = \frac{1}{L} \sum_{j=1}^{m} L_{ut,j} \left( w_j, M, r_j, \alpha_j, V_{S_j}, d_j \right),$$

where: $L$ is the total usable length of the railway network (namely sum of length of all the network elements, that can be operated), $j = 1, 2, \ldots, m$ are numbers of critical objects in railway systems (such as railway station, bridges, tunnels, etc.) and segments of tracts between the critical elements, $L_{ut,j}$ is the unusable track length caused by damage of the “$j$” object, $w_j$–weighting coefficient (depending on the structural solutions, lifetime, time since last restoration or maintenance / repair, actual conditions, etc. determining the damage of the given $j$-th object), $M$ – magnitude of the earthquake, $r_j$ – distance of the given object from the centre of earthquake, $\alpha_j$ – angle between the rupture propagation and mean axis of the object, $V_{S_j}$ – shear wave velocity, that is a soil measurable mechanical property, and $d_j$ – is a statistical damage coefficient.

In Equation (8) $M$, the earthquake magnitude is a major parameter that defines the area affected by earthquakes. Methods for evaluation of the magnitude of earthquakes or propagation of born waves are well developed and available in references (Stein & Wysession, 2005), (Wesnousky, 2006), (Hori, 2018). In case of having available data from a large number of distributed sensors measuring the ground motions in case of earthquakes (Silacheva, Kulbayeva, & Kravchenko, 2014), Equation (8) can be approximated by semi empirical formulas. However, it is still a very complex task, which depends on too many parameters and complex behaviours. The seismological observation system of Kazakhstan (Figure 20) includes 60 observation posts, 50 of which are seismic stations; a network of seismic stations of the National Nuclear Center of the Republic of Kazakhstan.
The area affected by earthquakes might be determined from the large number of distributed sensors (Fig. 21.) data directly (Okada, et al., 2004), (Okada, 2013) by using sensor fusion. Wider scale measurements of ground motions and using data from space sensing may improve the rapid analysis of the areas affected by earthquakes (Акимов, 2016), (Schröter, Kiefl, Neidhardt, Gurczik, & Dalaff, 2020). In case of a lack of available data, a simple method might be used based on the data published by (Seizmology, 2020). According to the publication, in case of a magnitude M = 7 earthquake occurrence, at which the damages must be estimated, the area covers 30 x 30 km, in which the average displacement equals to 1.5 m and average time of the event is 10 sec.

The effects caused by earthquakes depend on the soil’s properties. As it is well known, the soil depending on the shear wave velocity can be classified as (a) hard rock (igneous rock), (b) rock (volcanic rock), (c) very dense soil and soft rock (sandstone), (d) stiff soil (mud), (e) soft soil (artificial fill) and (f) soils requiring site-specific evaluations.

The damage to critical objects (influencing large parts of the railway systems), of course, depends on the structure, actual conditions of the infrastructure, etc. The damage to
infrastructure depends on the position of rupture propagation line to the mean axis of the object as it was introduced in Equation (8).

Formula (8) can be used in two steps. At first, the unusable element “j”, then the unusable length of track must be identified.

There are three possible ways that can be applied to estimate the relative unusable objects:
- direct information from the integrated sensors (Fraga-Lamas, Fernández-Caramés, & Castedo, 2017);
- using earthquake records for physics-based prediction (Evangelista, et al., 2017), the size of zone with ground motion (acceleration) crossing the limits (defined for damage occurrence),
- applying empirical fragile functions (Baker & Eeri, 2019), (Foytong & Ornthammarath, 2020).

Principally, the equation (8) can be approximated by a simple linear regression model (Urrutia, Bautista, & Baccay, 2014). The more complex models, like fragility curves and damage probability matrices express the probabilities that a structure will sustain different degrees of damage at given ground motion levels (Singhal & Kiremidjian, 1996), (Despotaki, Burton, Schneider, & Burton, 2017). Naturally, the fragility curve plotted between earthquake intensity and damage grade in terms of the conditional cumulative probability of reaching a certain damage state is a well understandable curve, yet it can only be applied as a semi empirical equation. In this case we must assume that the distribution of structural damage data agrees well with the lognormal distribution (Nagethi-A. & Shashavar, 2004):

\[ F(a_g) = \Phi \left( \frac{\ln(a_g)}{\mu} \right), \]  

(9)

where \( F(a_g) \) is the seismic fragility function, \( a_g \) indicates the amount of ground motion (PGA or PGV), \( \sigma \) is the average natural logarithm of the input motion levels, \( \mu \) is the natural logarithmic standard deviation of the input motion levels and \( \Phi[.] \) is the standard normalized distribution function.

The parameters of the models can be estimated by using well-known formulas.

\[ \ln \bar{\sigma} = \frac{1}{n} \sum_{i=1}^{n} \ln a_{gi}, \]  

(10)

\[ \bar{\mu} = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \ln \left( \frac{a_{gi}}{\bar{\sigma}} \right)} . \]  

(11)

This model may approximate the available data well (Baker & Eeri, 2019), but it can only is applied to the given region (with given natural environment (seismic activities, soil features) and infrastructure having given structural solution and applied materials.

The second step in determining the \( L_{ut} \) is estimation of the unusable track lengths, \( L_{utj} \), blocked by damaged objects, tracks. It is a simple task. The \( L_{utj} \) equals to the length between the starting and finishing the roundabout (bypass) because of the blocked area by damage of “j”-th object.

In case of using another index, like the relative number of people that cannot access the railway or cannot be evacuated, the number is harder to determine. For example, when the railway bridge is destroyed, that blocks rail transport through the river, while people can be evacuated using the dead-end sidings operation.
This model may approximate the available data well (Fig. 22), but it can is applied to the given region (with given natural environment (seismic activities, soil features) and infrastructure having given structural solution and applied materials.

In a more general form, applicability of the transport systems is usually analysed and evaluated by the use of different modelling and simulation methods (Chang, Elnashai, Spencer, Song, & Quyang, 2010). According to the railroad damage a semi – empirical approach based on utilized GIS (geographic information system) maps (ESRI, 2007), (Rusydy, et al., 2018) might be used for expert definition of the relative unusable track length in the following way (Figure 30.):

- preliminary actions: create GIS map containing the railway systems, identify critical objects, geographical map of soil with different shear-wave velocities and statistical data about the previous earthquakes and damages caused by them;
- after getting the information on the current earthquake, the affected areas can be marked in a preliminary prepared GIS map;
- identification of the objects affected or those that might be affected by earthquakes, evaluation of the actual situation and calculation of the possible damages;
- calculation of the length of railroads affected by the damages of the given j-th objects;
- determination of the identification of the critical function describing the damages.

The same maps can also be used for evaluation of the risk of secondary effects.

From the disaster management point of view, sub-model 1 provides the first information about the size of damage and required recovery actions. This is a model of the first order, so it can be changed by getting new information including information of special measurement means, for example by using drones to estimate the real damage of the critical objects.

In the event of earthquakes and other natural disasters in the Republic of Kazakhstan, for the State system for the prevention and liquidation of emergencies, the main problem remains as the lack of timely and reliable information about emergencies (Халиков, Шарипханов, & Муканов, 2008).

Analysis of the experiences of using UAVs in the USA and in a number of other technologically developed countries in order to obtain timely information and to conduct various operations, including rescue operations, showed good results (Серкпаев & Ибраев, 2015). UAV’s might
be applied to the disaster monitoring very widely (Giglio, et al., 2008), (Restás, 2015), (Kerle, Nex, Gerke, Duarte, & Vetrivel, 2020).

The response must be started by recovering the object to the operational level, in which

\[
C_{c_q} = \frac{\Delta l_q}{c_q} \rightarrow \max \quad \text{or} \quad C_{w_q} = \frac{\Delta l_{ut_q}}{w_q} \rightarrow \max
\]

\[
C_{t_q} = \frac{\Delta l_q}{t_q} \rightarrow \max \quad \text{or} \quad C_{p_q} = \frac{\Delta n_{p_q}}{t_q} \rightarrow \max
\]

where: \( q = 1, 2, \ldots, s \) – number of critical objects destroyed, \( C_q, W_q, t_q \) cost, works and time needed for recovery to the operation level of the \( q \)-th object, \( c, w, p \), indexes depict the cost, work and people (can be evacuated) supporting the recovery processes, \( \Delta l_{ut} \) decreasing \( l_{ut} \) to recovery, \( \Delta n_{p_q} \) defines the changes (decreasing) of the number of people that cannot be evacuated.

From the modelling point of view, the damage recovery process of the total process, or different objects, systems elements can be modelled, too, by using the Markov model based on the equations (3) – (6).

Figure 23. Using GIS supports the estimation of the possible secondary effects, damages and determination of the relative unusable track length.
The Markov models can be applied to the railway systems in general approximating the changes in relative unusable track length, $l_{ut}$ or to a group of objects (like railway stations of a large town or city) and even to one major element (such as a bridge). In all the cases, the models are developed in the following ways:

- the elements of the transition matrix can be determined by using the practical data, the time ($t_{ij}$) spent to change the object (or system) currently in the given $i$-th state into the state $j$:

  $$\beta_{i,j} = \frac{1}{t_{ij}},$$  \hspace{1cm} (13)

- $\sum_{i=1}^{n} P_i(t) = 1,$  \hspace{1cm} (14)

- $\beta_{i,i} = -\sum_{j=1, j\neq i}^{n} \beta_{i,j}(t),$  \hspace{1cm} (15)

Figure 24. Modelling the railway stations’ recovery to operational level after an earthquake

Figure 24. shows the recovery process of the railway stations damaged by an earthquake to the operational levels. There are five railway stations in the city. The general damage is 84%. That means there is 80% probability that four railway stations cannot be operated and 20% probability that all the five stations are out of operation. The recovery process is based on the Markov model described above. The transition matrix is assumed to be constant and the elements are determined from the available data on the earthquake (G.William Byers, 2000).

As it can be seen (Figure 24.), all the railway stations can be returned to the operational level with more than 60% probability after 11 hours, and in 24 hours all the stations can be operated with 90% probability (here the aftershocks and secondary effects are not taken into account).

2.3. Probabilistic model of aftershocks

Earthquakes do not occur as a single event. Several, or sometimes even more of, so-called aftershocks follow the earthquakes. These are – as a rule – smaller in magnitude, and may follow the earthquake after some minutes, some hours or even some days. For instance, after the Great East Japanese Earthquake over 130 aftershocks occurred on the same day, and later more than 400 greater than 5 M, (Edwards, et al., 2015). During 6 days after Augustus 24, 2016, Central Italian Earthquake more than 2500 aftershocks were recorded, from which more than 10 reached the level magnitude 4 (Wikiwand, 2020).
Many studies are dealing with aftershock. The first well-applied and simple model was introduced as the simplified model of Fusakichi Omori in 1894 and is known as Omori’s law (Omori, 1894):

\[ n(t) = \frac{k}{c+t}, \]  

(16)

where \( k \) and \( c \) are constants, which vary between earthquake sequences. Most used modification of this formula (20) was proposed by Utsu in 1961 (Utsu, 1961):

\[ n(t) = \frac{k}{(c+t)^p}, \]  

(17)

where \( p \) is a constant, that modifies the decay rate and typically falls in the range 0.7–1.5.

Another applicable mode is the Gutenberg – Richter (GR) model (Gutenberg & Richter, 1934):

\[ \log_{10} N = a - bM, \]  

(18)

where \( N \) - is the number of events having a magnitude equals or greater than earthquake magnitude \( M \), \( a, b \) – are constants.

The models introduced here, are combined into a following statistical model of aftershock rate, \( R \), developed by Reasenberg and Jones (Reasenberg & Jones, 1989).

\[ R = 10^{a+b(M_{\text{main}}-M)}(T+c)^{-p}, \]  

(19)

where, rate \( R \) of aftershocks of magnitude \( M \), at time \( T \) after a magnitude \( M_{\text{main}} \), while \( a, b, p \), and \( c \) are model parameters representing the regional aftershock productivity, scaling of aftershock rate with mains-hock magnitude, the decay of the rate of aftershocks with time and time scale of the earliest part of the sequence before it starts to decay, consequently. The constants \( a, b, p \), and \( c \) are often called as Omori values.

The \( R \) rate is a function of time, \( t \), and time-dependence magnitude of completeness, \( M_c(t; M_{\text{main}}) \) that can be defined as

\[ M_c(t; M_{\text{main}}) = \max \left\{ \frac{M_{\text{main}}}{2} - G - \log_{10}(t) \right\}, \]  

(20)

Here \( G \) is constant and \( M_{\text{cat}} \) is the known completeness of the catalogue when a large earthquake has not recently occurred.

The model (19) was extended (Page, van der Elst, Hardebeck, Fedzer, & Michael, 2016) to apply globally by grouping tectonically similar areas together, using the tectonic regionalization and determining parameter values for each global tectonic regime.

Page and his colleagues (Page, van der Elst, Hardebeck, Fedzer, & Michael, 2016) also found the productivity parameter \( a \) for each main-shock in each tectonic regime. They recommend using the \( a \)-values with a normal distribution. Such distribution can be used for forecasting with uncertainty bounds that reflect the parameter uncertainty, as well as random variability.

Unfortunately, all these models have at least two weaknesses:

- they cannot give accurate and general approximation because of the large uncertainties in the parameters,
- they are not giving information on the place of occurrences of aftershocks.

Figure 25. shows time-dependent magnitude of completeness and Figure 26. demonstrates that, the model (23) might be applied to aftershock forecast with time-depending Omori values.
Figures 27, 28, and 29 explain the real difficulties in using simple forecast models for aftershocks predictions. At first, there are several shocks that appeared before the main earthquake with magnitude of 6, and the aftershocks were occurring continuously in large number with rather wide range of magnitudes as it summarizes by Table 5. The second figure (Figure 28) shows that, the aftershocks are distributed in a wide range of land.

At first, this methodology takes into account the predicted aftershocks with magnitude of 4 or greater, only. Effects of an aftershock, generated in simulation at the given k time step, might be estimated by the same ways as the effects caused by earthquakes. As usually, the aftershocks increase the relatively unusable track length.

Figure 25. Time-dependent magnitude of completeness analysis for all global aftershock sequences (Page, van der Elst, Hardebeck, Fedzer, & Michael, 2016). (Irregular curves in the left panels are running fits to the 50% completeness level $\mu_t$ for each mainshock magnitude range individually (time-window width is $0.5 \log$-time units). Dashed lines are model fits for $\mu_t$ assuming equation (24) and fitting the entire dataset simultaneously. Solid black lines show the assumed functional dependence of $M_c(t;M_{\text{main}})$, given by equation (24) with $G = 0.25$ and $M_{\text{cut}} = 4.5$. Right panels show individual magnitude distributions for successive time ranges as a function of mainshock magnitude. Dashed lines are the model fit to the entire dataset.)
Figure 26. Posterior distribution example using the 2010Mw 8.8 Maule, Chile, earthquake. Immediately following the earthquake, the region-specific Omori a-value distribution can be applied to aftershock prediction (Page, van der Elst, Hardebeck, Fedzer, & Michael, 2016). Geographical distribution of aftershock can be modelled by using an ellipse direction of which follows to faults (Fig. 29.).

Figure 27. Magnitude of the Central Italy earthquake (6.0) and its aftershocks (most were less than 4.0); aftershocks continued to occur after first earthquake until next large earthquake with magnitude of 6.5 (Wikiwand, 2020). Table 5. Earthquakes with magnitude greater than 4 in August 2016 Central Italy earthquake (Wikiwand, 2020)
Figure 28. Aftershock distribution map, 24–25 August. (Red: Main shock, Orange: 4.0–5.9, Blue: 3.0–3.9, Light blue: 0–2.9), (Wikiwand, 2020)

Figure 29. Example of model ellipse fitted to aftershock sequences. (The ellipse contains approximately 90% of the plotted events. The 1964, MW = 9.2, Alaskan earthquake and aftershocks. Epicentres of 243
earthquakes larger than magnitude 5.0 within 1103 km of the mainshock and 10 months after the mainshock are plotted. (Christophersen & Smith, 2000)

Figure 29. calls attention on a special distribution of probability density of occurrence of aftershocks in form of 4D at least. This means, the distribution depend on time (aftershock), intensity (earthquake module) and 2 dimensions of land (space).

On one side, the practical data on aftershocks can be shown in the form of a three-dimensional distribution (Figure 30). On the other hand, the location of the determined aftershocks (by using the Figure 30), might be estimated by using the two dimensional normal distribution of aftershocks in ellipse developed on the basis shown in Figure 29.

Unfortunately, there is no available information to estimate the three-dimensional distribution. Instead, the required distribution can be built by using (i) the observed seismic activities, hazard assessment and information on aftershocks detected during and after earthquakes. The latter is usually available only as a two-dimensional distribution (Guo & Ogata, 1997), (Silacheva, Kulbayeva, & Kravchenko, Probabilistic seismic hazard assessment of Kazakhstan and Almaty city in peak ground accelerations, 2018) (Rehman, Qadri, Ali, Al, & Ahmed, 2016). So, Figure 30 shows a semi-empirical, or semi-hypothetical model.

Finally, a Monte Carlo simulation can be applied. Four random values must be applied for determining the aftershock intensity and its location. The aftershock, its magnitude and location predicted for given time or a given k step of the simulation, and its effect, the increase in the relative unusable track lengths, $\Delta l_{u,t}$, must be determined using the same methodology as it was described for railway system damage caused by an earthquake.

### 2.4. Statistical model of secondary effects

An earthquake causes primary and secondary effects. The primary effects are the result of the surface rupture along the fracture and shaking caused by the earthquake’s energy. The secondary effects are caused by primary effects and can turn up as a tsunami, landslide, fires, flood, industrial catastrophes, or epidemics. Table 6. helps to understand the different types and sizes of the aftershocks.
### Table 6. Some examples of typical aftershocks (information is taken from Wikipedia and Google map)

<table>
<thead>
<tr>
<th>№</th>
<th>Magnitude, year, location of the earthquake</th>
<th>Earthquake area and epicentre</th>
<th>Description of secondary effects caused by earthquakes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M 8.6 - 1946 Aleutian Islands (Unimak Island) Earthquake, Alaska</td>
<td><img src="image1" alt="Map of Aleutian Islands" /></td>
<td>Casualties: 173 people killed. Total damage: $26 million. <strong>Tsunami:</strong> earthquake occurred at Aleutian Island, Alaska and caused a tsunami with multiple destructive waves that 4.9 hours later killed 173 people in Hilo, Hawaii. Maximum rise of water was as much as 17 m on the Island of Hawaii. The water rose about 5.1 m at the mouth of the Wailuku River.</td>
</tr>
<tr>
<td>2</td>
<td>M 8.6 - 1950 Assam-Tibet Earthquake</td>
<td><img src="image2" alt="Map of Assam-Tibet" /></td>
<td>Casualties: 4,800 people killed. <strong>Landslides:</strong> in the Arbor Hills 70 villages were destroyed with 156 casualties <strong>Flood:</strong> large landslides blocked the Subansiri river and a natural dam was broken 8 days after the earthquake. A wave as high as 7 m (23 ft) inundated several villages and killed 536 people.</td>
</tr>
<tr>
<td>3</td>
<td>M 9.2 - 1964 Prince William Sound Earthquake, Alaska</td>
<td><img src="image3" alt="Map of Prince William Sound" /></td>
<td>Casualties: 131 killed. Total damage: $311 million. It was the second most powerful earthquake recorded in world history. 970 m of fault ruptured and moved up to 18 m. <strong>Soil liquefaction, fissures, landslides, and other ground failures</strong> caused major structural damage. Large underwater landslide killed 32 people and collapsed Valdez city harbour and docks. <strong>Tsunami:</strong> it caused serious damage to the railroad facilities at Seward Port, where rails were stripped from the railroad. Most of the Alaska Railroad dock was washed away by the waves. The railroad also lost two cranes and its waterfront tracks. Post-quake tsunami caused damage in Hawaii and Japan, too.</td>
</tr>
<tr>
<td>4</td>
<td>M 9.1 - 2004 Sumatra-Andaman Islands Earthquake (undersea megathrust earthquake)</td>
<td><img src="image4" alt="Map of Sumatra-Andaman" /></td>
<td>Total damage: US$15 billion. <strong>Tsunami:</strong> A series of massive tsunami waves grew up to 30 metres (100 ft) high, heading inland after being created by the underwater seismic activity offshore. Communities along the surrounding coasts of the Indian Ocean were severely affected, and the tsunamis killed 227,898 people in 14 countries.</td>
</tr>
</tbody>
</table>
The role of secondary effects can be understood from the available statistics. The top 10 earthquakes in terms of fatalities show that primary and secondary effects caused 66% and 34% of fatalities, respectively (Daniell, Schaefer, & Wenzel, 2017). Of course, the statistics includes the events such as the Indian Ocean Earthquake in 2004, when 99.5% of killed people (227,898 deaths in 14 countries) were due to tsunami; or earthquakes of 1948 in Ashgabat and of 2010 in Haiti, during which the deaths caused by the secondary consequences were zero. From the point of view of disaster recovery management, there is an important difference between the primary and secondary effects of earthquakes. Earthquakes last from several seconds up to several minutes, while the time of the secondary effects and damages caused by them may take from 15–30 minutes to hours. In some cases, this time may even grow up to a few days (see Table 1. 1950 Assam-Tibet Earthquake).

Post disaster situations can be determined from the changes in the tension in the upper crust around the fault rupture that can influence the behaviour of neighbouring faults and volcanoes (Béjar-Pizarro, et al., 2018).

The determination, estimation and analysis of the secondary effects can involve two steps. At first, prediction of the secondary effect appearance can be done due to the available historical data or evidence. For example, earthquakes that occurred underwater were usually (with 100% precision) followed by a tsunami.

The second step is to study the motion of the secondary effects, e.g. how much time passes before the flood, the motion of tsunami waves, (Kia, et al., 2012) (Wikipedia, 2020), (Saito & Furumura, 2009), (Bagiya, et al., 2017).

Such simulations and calculations may require serious competencies in simulation technologies. Therefore, these methods must be applied during the phase of preparedness or in their very simplified forms in order to support the recovery process management.

On the other hand, the so-called engineering effects, the design of buildings and operation of constructed environments play a considerable effect, resulting in nearly 13% of fatalities (of the top ten earthquakes). At the same time, there are many laws developed and requirements related to the engineering design of buildings, houses, road infrastructure, energy generation stations, etc. to make them earthquake resistant. Now it is time to develop similar laws and requirements taking into account secondary effects of earthquakes.

2.5. Situation awareness – decision making
Equations (3) – (6) define the Markov chain process approximating the damage – recovery process (of railways). In practice, the process is controlled by the managing actions.

The response is started by getting information about the damages caused by the occurred earthquake. It seems that this first state as an initial situation is well observable. However, even this first information may contain false, inaccurate and uncompleted information about the condition of the critical elements, about the damage in infrastructure. After the evaluation of this first situation, several actions can be identified. Of course, when an earthquake damages several railway stations, bridges, tunnels and trucks in dozens sites, the recovery process – because of limited available sources – can be started by different actions and different rules.

According to this principle, the recovery process – depending on the response manager decision – can be started by rebuilding bridges and/or building an interim pontoon bridges, then following by recovery of the most important railway station, working on repairing the trucks at sites allowing the establishment of shortcuts, etc. All the actions can be defined as states, \( s \in S \) characterised by required (predicted) time, cost, work etc. Of course, all the possible actions can be defined as state.

By introducing this approach, namely constructing or approximating the recovery process of continuous time and continuous space by well-known stochastic discrete time, discrete space process, the recovery process is modelled by the controlled Markov process.

Decision making of recovery managers is recommended to be supported by using methods of subjective analysis (Rohacs, 2012), (Kinzhikeyev, 2020). Manager, as a subject, must identify and understand the problem (situation), \( s_i \), then from the set of accessible or possible devices, methods and factors, \( s_p \), must choose the disposable resources, \( R^{\text{disp}} \), available for the possible solution of the identified problems, and finally must decide and apply the required resources, \( R^{\text{req}} \). As it was figured, the recovery manager utilizes passive and active resources (Касьянов, 2007). The active resources are defined by manager’s decision on which and how will the passive resources be used: \( R^{\text{req}} = f(R^{\text{p}}) \).

It is clear that the recovery processes can be given by a series of situations: manager identifies the situation, \( s_i \), makes a decision and applies the control, \( R^{\text{eq}}_a \), which transits the process into the next situation, \( s_j \), randomly. (The situation, \( s_i \), is one of the sets of possible situations). This is a repeating process, in which the transition from one situation into another depends on (i) the evaluation (identification) of the given situation, (ii) the available resources, (iii) the appropriate decision of the response manager, (iv) the correct application of the active resources, (v) the limitation of the resources and (vi) the affecting disturbances. The situation chain process can be given by the following mathematical representation (Касьянов, 2007).

\[
c(t) = \begin{cases} (x_0, t_0, \sigma(t_f \in [t_0, t_0 + \tau]), R^{\text{disp}}(t_0), R^{\text{req}}(t_0),...) \end{cases}, \tag{21}
\]

or in a more general approach:

\[
c(t) = \begin{cases} (P; \sigma(\sigma_0(t_0) \rightarrow \sigma(t_f \in [t_0, t_0 + \tau]) \in s_f \in S_a, R^{\text{disp}}(t_0), R^{\text{req}}(t_0),...) \end{cases}, \tag{22}
\]

where \( x_0 \) is the vector of parameters at the initial (actually starting) state at \( t_0 \) a time (here it is the \( t_{\text{ut}} \)); \( \sigma \) is the state of the system in the given time; \( \tau \) is the available time that is enough for a transition of state vector into the set of \( \omega \) not later than \([t_0, t_0 + \tau]\); \( P \) are the problems of how to transit the system from the initial state into one of the possible states \( s_f \subset S_a \) not later than \( \tau \).
By introducing this description, two new aspects appeared. At first, the manager decision process is an active endogenous system (Kasьяннов, 2007), (Kasianov, 2013), (Rohacs, 2012), (Kinzhikeyev, 2020). The system is active because the operator managers actively generate the control inputs depending on their decision. At the same time, the operator managers are the elements of the total management systems, therefore their actions, as control inputs origin from inside the systems. Such systems are endogenous.

In case of a highly automated system, the role of situation awareness – evaluation and subjective decision increases. Therefore, the conventional and well known model of Endsley (Endsley M. R.; Rodgers M. D., 2016) was improved by including the “Present Situation”, total load systems, as well as extending the “Task/System Factors” and “Individual Factors” into the general situation awareness model (Rohacs, Rohacs, & Jankovics, 2016), (Jankovics I.; Kale U., 2019), (Kale U., 2019)

Secondly, the initial Markov chain process becomes a controlled Markov process that might be used as a Markov decision process (MDP) (Puterman, 1994) supporting the response management (Ghosh & Gosavi, 2017). Therefore, the situation chain process (21) and (22) can be given in form of MDP process.

Such process is required to solve the optimization process of the mathematical representation of which is the following (Todorov, 2006), (Gol, Erkal, & Gol, 2019), (Yu, Han, & Ma, 2014):

\[ s \in S \text{ or } (x \in X) : \text{states of the process where } S_t = s; S_t+1 = s', \]
\[ u \in U(s) : \text{actions/controls applicable to the given process}, \]
\[ P\{s_{t+1} = s' | s_t = s, u_t = u\} : \text{transition probability matrix, that represents the probability of transition of the process from state } s_i \text{ to the next } s_j \text{ state, by applied action } u_i, \]
\[ R(s, u) \geq 0 : \text{real-valued immediate (or expected) reward received during transition of the process from state } s \text{ to } s_j \text{ by applied action } u_i, \]
\[ R_{\tau}(s) \geq 0 \text{ scalar cost at terminal states } s \in T, \]
\[ \pi(s) \in U(s) : X \rightarrow U : \text{control law policy, fixing the action / control for each state of controls.} \]

Here policy is a function that specifies the action \( \pi(x) \) that the decision maker will choose when the state \( x = x_i \) is identified.

\[ v^\pi(s) \geq 0 \text{ value (so called cost to go) function calculated as cumulative cost for the process starting at state } x \text{ and acting according to } \pi \text{ applied thereafter.} \]

\[ \pi^\star(s), v^\star(s) – \text{are the optimal control law and corresponding function.} \]

This defined dynamic decision problem modelled as Markov decision process is obviously a sequence decision process. The optimal value and control can be determined from the following equations:

\[ v_t^\star(s) = \max_{u \in U} \left[ \sum_{s' \in S} P(s, u, s') [R_t(s, u, s') + v_{t+1}^\star(s')] \right], \quad (23) \]
\[ \pi_t^\star(s) = \arg\max_{u \in U} \left[ \sum_{s' \in S} P(s, u, s') [R_t(s, u, s') + v_{t+1}^\star(s')] \right]. \quad (24) \]

The MDP can be solved by using the value and policy iteration, Monte Carlo planning algorithm using bandit algorithm, or different learning methods (Bellman, 2003), (Howard, 1960), (Puterman, 1994), (Kocsis & Szepesvári, 2006). Several softwares are available for supporting the application of MDP as Python Markov decision process toolbox (Python, 2020) or Mat lab toolbox (Cros, 2020).

While some papers show that the MDP can be applied for the restoration of a distribution system damaged by an earthquake (Gol, Erkal, & Gol, 2019), (Tao, Wang, Ellingwood, &
Nicholson, 2020) (Arpali, Yilmaz, Gol, Erkal, & Gol, 2019), others states that, the MDP is “...too quantitative and computer-driven to be effective in all disaster scenarios (Boin et al. 2005), because disasters often occur within complex social settings and scenarios which evolve without necessarily corresponding to probabilistic factors” (Fakuade, 2017).

In case of using the MDP to response management to earthquake damage, another important aspect calls for special attention and introduces serious barriers. During response, the transition probability matrix, rewards, possible actions, as well as the value and control of low policies are changing radically and randomly, which is caused by aftershocks and secondary effects. The response management methodology developed and recommended by this paper eliminates this disadvantage by regular revision of the required inputs for applied simulation.

3. Active adaptive response management
3.1. Concept development
The disaster recovery management is a set of rules and procedures focusing on the reduction of the disasters’ consequences. It includes all the related activities that occur prior to, during, and after a disastrous event. As it was stated, the developed response management synthesizes management art with methods of applied sciences, available technologies and engineering approaches. This methodology deals with the railway system recovery, only. Therefore, it uses more engineering than managing approaches, but it requires the creation of managing decisions, too and is, in each step, supported by simulation process.

There are many materials published, that describe the general disaster recovery process with applicable approaches and methodology to follow (United, 2016), (FEMA, National Disaster Recovery Framwork, Second Edition, 2016), (Council, 2020). These booklets are very important, because like the National Disaster Recovery Framework (NDRF) (FEMA, National Disaster Recovery Framwork, Second Edition, 2016) they establish a common platform and a forum where it is prescribed how the whole community needs to build, sustain, and coordinate recovery activities.

The recovery management methodology, in question, determines the recovery of the railroad and railway system in case of an earthquake disaster. This management is based on the goal and object oriented application of the sub-models described above in the previous chapter.

The disaster management, of course, deals with the study of the available historical data, risk analysis, risk mitigation, preparedness and warning (Fig. 1). These important elements of disaster management result in preparedness. In terms of railroads, it means that the possible seismic effects (Figure 20.) using simulation methods can be studied. This study may deal with possible monitoring of the damage by using series of sensors integrated into the critical elements, like bridges, tunnels and using such active monitoring systems as drones measuring and collecting data on damage sizes (Moreu, Kim, & Spencer Jr., 2016), (Fraga-Lamas, Fernández-Caramés, & Castedo, 2017). Such simulation may lead to a development of the regulations and requirements for design, operation, required technology supports, etc. All of the above shows where and what types of spare parts must be reserved for quicker recovery of the damaged railroad.

This paper deals with technical recovery management only (launching the recovery process), that is initiated by getting information about the earthquake that has just occurred. The management is completed form recurring cycles including zero + six + one steps (Figure 31.) and is based on using the sub-models defined above. The role and meaning of the steps can be defined shortly by the following ways.

Step 0. Preparedness – using historical data on previous disasters, nature, infrastructure, economy and society, simulation studies that result in
- technological preparation (determination and usage of rules, requirements, creation of systems of distributing required spare parts for damage repairs, etc.,
- development of information system and general (GIS) map.

In this section, we propose the creation of geographic information platform of special purpose. This is a Bank of geospatial information that will collect digital cartographic data, aerospace survey data, infrastructure information about the territory, land, air, water transport and material resources by industry, materials on certification of objects that are vulnerable to natural disasters, historical data on previous disasters, etc.

GIS platform should provide the controls of transport, emergency and other departments’ objective and operational information. This will reduce the time to collect terrain data and increase efficiency in the evaluation of district disaster and decision-making. In an emergency situation, this will give rescue teams a significant advantage and allow them to exchange information and monitor the situation in real time.

An approximate version of the plan - prospectus for describing railway transport, which is shown Table 7.

Table 7. An approximate version of the plan - prospectus for describing railway transport
<table>
<thead>
<tr>
<th>Section number</th>
<th>Section name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section I</td>
<td>General characteristics of railway</td>
<td>- Geographical location of the railway, the total area of the served territory, population, average road density; - The administrative division of the railway and their borders; - railway length and their characteristic (km); - name, number and class of railway stations.</td>
</tr>
<tr>
<td>Section II</td>
<td>Railway throughput</td>
<td>The railway scheme indicating the throughput, size of movement, weight and length of trains and locomotives used including: - the throughput of sections, connecting branches and bypasses of nodes by elements; - unified and precinct weight standards (s), train lengths; - precinct and technical train speeds (km / h) in directions.</td>
</tr>
<tr>
<td>Section III</td>
<td>Technical characteristics of railway</td>
<td>a) The railway scheme indicating the types of rails, sleepers and kind of subgrade; b) the scheme of sections railways prone to precipitation, erosion, landslides, snowfalls; c) a list of permissible speeds and maximum loads on the railway track.</td>
</tr>
<tr>
<td>Section IV</td>
<td>Locomotives</td>
<td>a) railway scheme indicating types of traction, types of locomotives and locomotive depots; b) a scheme indicating the warehouses, equipment points and water supply of locomotives; c) the scheme of external power supply of electrified sections of railway; d) the number of locomotive fleet by type.</td>
</tr>
<tr>
<td>Section V</td>
<td>Wagons</td>
<td>Scheme of the main railway network with the indication of the production units of the wagon economy, including: - car building and car repair plants; - car depot, washing, water supply, disinfection and wagon equipment points.</td>
</tr>
<tr>
<td>Section V I</td>
<td>Communication and alarm, centralization, blocking devices</td>
<td>a) Railway scheme indicating the types of communication, including: - telephone and telegraph, inter-office, dispatch and their characteristics; - radio and radio relay stations, their type, number of channels; b) Railway sections equipped with dispatch centralization, auto-lock, semi-automatic lock, electric wand system.</td>
</tr>
<tr>
<td>Section VII</td>
<td>Computer Center and Automated Control System</td>
<td>Information and communication scheme of the automated control system of the railway network, including: - computer centers and location; - information connection of railway network computing centers with productivity; - technical means of automation.</td>
</tr>
<tr>
<td>Section VIII</td>
<td>Loading and unloading places and devices</td>
<td>The scheme of the railway network indicating the loading and unloading places and devices, including: - loading and unloading places indicating railway stations, stationary, temporary, their loading rate; - loading and unloading platforms (lateral, end, combined), their sizes, their loading and unloading ability (wagons / day); - container sites, their size and processing capacity (cont. / day).</td>
</tr>
<tr>
<td>Section IX</td>
<td>Material and medical support</td>
<td>a) The railway scheme indicating the material support devices, including: - points of water, coal and firewood supply; - bakeries, canteens and restaurants available at the stations, their productivity, number of seats. b) Railway scheme with medical devices.</td>
</tr>
<tr>
<td>Section X</td>
<td>The relationship of the railway with other modes of transport</td>
<td>a) Railway scheme indicating the points of transshipment to other modes of transport (sea, river, road, air, pipeline); b) the characteristics of the butt points (sea and river ports, pipelines, roads, railway access, roads to airports, etc.). c) characteristics of railway ferries.- ferry crossing capacity (wag / day).</td>
</tr>
</tbody>
</table>
Sergey Kinzhikseyev  
Modeling recovery of railway system after earthquakes

| Section XI | Construction and repair organizations | Railway scheme indicating construction and repair organizations: - their name and subordination, location; - fire trains; - logging and woodworking enterprises, their productivity; - quarries and crushed stone plants and their resources (thousand m3) and productivity. |
| Section XII | Opportunities for railway recovery arrangements | a) Scheme with engineering and technical measures of the railway: - options for bypassing nodes and bridges; - design considerations for the restoration of critical railway facilities;  
b) The scheme of restoration of electrified sections of the railway;  
c) a diagram indicating the flood zones of railway sections;  
d) Stock list of reducing materials and structures. |

| Part Two: “Railway Station” |
| Schemes and profile of railway units, stations, their names, characteristics, classes, types and equipment. |

| Part Three: “Bridges and Tunnels” |
| Bridge Information | a) railway scheme with bridges, passports, plans, profiles and characteristics of bridges, field;  
b) Tunnel schemes, passports, plans, profiles and characteristics of tunnels, location. |

3.2. General management process

Step 1. Collecting and evaluating the information

There are three major areas that must be investigated:

- the earthquake, using the sensor network and special measurements (for example collecting information by using drones);
- evaluation of the available measures and collected data (data processing, e.g. sensor fusions);
- population and the economy affected.

Railway sections and structures may have different levels of earthquake resistance. Sometimes, damage to one element can lead to the failure of the entire facility or to an environmental disaster, in connection with which data collection is necessary for planning organizational and engineering activities (К.Касымов, 2014).

In connection with this, the next step proposes integration of data on the state of transport objects according to the following scheme: seismological observation system → seismic sensors at transport objects → drones → railway monitoring system (Fig. 32).

To obtain information about the state of transport objects, it is necessary to install sensors on them, placing them linearly along the railway line, which will make it possible to diagnose damage and condition of sections of railway tracks, bridges, tunnels, ballast, avalanche sites, etc. In addition, these sensors can be used to detect damage in the event of other natural disasters, which can also lead to damage to vehicles. The arrangement of sensors should provide:

- automatic response mode;
- data mining;
- efficiency and reliability of information;
- identification of facts about the development of destructive processes;
- the ability to work offline and the stability of the work after strong shocks;
- the possibility of development, expansion and integration with other systems.
All information received must be archived. When sensors are located on railroad facilities, their provision with electricity will be quite easy, but in addition to this, the use of emergency power sources due to renewable energy sources such as wind and sun is proposed. Redundant energy sources are very important to ensure system’s operability in the event of catastrophic shocks. Regarding Kazakhstan, the sensors installed at transport facilities can be integrated with the existing system of seismological observations (Figure 33.).

In Kazakhstan, the system of seismological observations includes:
- 60 observation points
- 50 of which are seismic stations;
- A network of seismic stations of the National Nuclear Center of the Republic of Kazakhstan. Currently, a digital network is functioning in Almaty and its environs, which includes 15 sets of digital accelerographs with a wide dynamic range that operates in a trigger mode with three-component registration.

Sensors for monitoring constant bridge loads and recording information before, during, and after earthquakes shown in figure 34.
The principle of operation of the sensors consists of following through the load pins and the data acquisition module installed on the bridge. The loads on the main bridge structures are measured and the measurement results are transferred to the data collection module of the industrial base station, which records them on a portable computer and transfers them to the storage cloud.

The use of drones during earthquakes will allow real-time exploration of a significant length of railway lines, as well as to track the occurrence of secondary effects of earthquakes (fires, debris, soil erosion after mudflow and floods, etc.). In addition, UAVs in comparison with space monitoring have an advantage in cost, for example, the financial costs of a project to create space monitoring of Kazakhstan earthquake areas as of July 2006 was up to $25 billion 11 million («Казкосмос», 2006).

The USA experience in using drones to obtain timely information during various operations, including rescue, showed high results (Серкпаев М.О., 2015). In 2020, during floods in Russia, the Russian Railways Ministry of Defence, an experiment was conducted on exploration of blurry sections of railways using UAVs, while UAVs of medium and light classes showed high efficiency (Fig. 35).

Figure 34. Sensors for monitoring constant bridge loads (Interface force measurement solutions, 2020).

Figure 35. UAV of the railway troops of the Ministry of Defence of the Russian Federation a.) “Tachyon” b) “Orlan-10” (Рамм А.; Степовой Б., 2020)
The main characteristics of the UAV:

1) “Tachyon” - light-class UAVs, length 0.61 m, wingspan 2 m, speed 120 km/h, maximum altitude 4 thousand m, maximum flight duration 2 hours, it allows video surveillance and carry out aerial and video shooting of the area at a distance of up to 40 km from the object; it is used both in the daytime and at night. The operating temperature range of the device is from -30 to + 40 °C. In addition, if necessary, it can be used as a relay of a communication signal.

2) “Orlan-10” - a middle-class UAV, has a range of 120 km. It is equipped with day and night video cameras, can transmits video online, the maximum duration of the flight is 14 hours, the maximum height is 5 thousand meters and the speed is 120 km/h. From one control centre, you can control the flight of four UAVs - this allows reconnaissance in several directions simultaneously. It is used to monitor long distance objects in hard-to-reach or remote areas, for example, in the Far East of the Russian Federation, due to the presence of difficult-to-access roads, motor vehicles cannot reach the scene of the accident quickly.

After the event, monitoring will help to assess the damage, determine rescue measures and means of recovery. Having received the necessary data, the Situation Centre of Railways analyses and summarizes them, gives the task of preparing a plan, on the basis of which the amount of forces and means involved to deal with natural disasters is determined.

Step 2. Information about the society and economy, constructions, infrastructures

During this step the information data processing must result in the

- estimation of the size of the area affected by the earthquake,
- determination of the disaster management objectives and prioritisation of the objectives (prioritisation can be made by other disaster management sub-committees, that may demand to evacuate the population from the given region first, therefore the given railroad has to be repaired first).

In previous steps, information was collected and data prepared, which is necessary to assess possible risks, create scenarios of possible disasters and conduct scientific analysis. Assessments of the effects of earthquakes, environmental sustainability and seismic risk assessments of territories exposed to hazardous, geological processes are among the most difficult problems.

Settlements in Kazakhstan that are located at the greatest seismically hazardous territories:

- East Kazakhstan region - 28 settlements (8-9 points);
- Almaty region - 98 settlements (8-9 points);
- Zhambyl region - 24 settlements (8 points);
- South Kazakhstan region - 15 settlements (8 points).

The territory of the city of Almaty, with a population of 1,916,822 people, can be affected by earthquakes of magnitude 9 or higher, therefore the city can be destroyed and the exit routes blocked (bridges, roads).

Only 30% of buildings will survive. Engineering communications will be less affected, although gas pipelines inside buildings may be damaged or destroyed, resulting in fires.

In the studied area (Almaty and the suburbs), there are about 1 thousand wooden apartment buildings and about 32 thousand individual wooden houses. From fires on the burnout area, 15% of residents of wooden houses who have suffered severe damage may die (Table 4).

In Almaty, there are 10 industrial enterprises working with ammonia and 1 plant with chlorine. In the event of an emergency, the area that could be affected is 11 square km, and about 72 thousand people could be live in this area.
The condition and capabilities of the railways are assessed in relation to evacuation measures and the transport of rescue teams to the disaster area. The capabilities of the railways are determined by the tasks, days and directions of transportation. This takes into account the nature of the degree of destruction of critical railway facilities, the effectiveness of engineering and technical measures that ensure the viability of transport facilities. Information for assessing the situation in the area of a natural disaster can be submitted to the Situation centre of the railway. A Situation centre of the railway is a technological complex designed for data collection and processing. It provides information support and ensures the organization's management activities in a dynamically developing environment (Ескандирова Д. М., 2017).

Recovery management consists of the targeted activities of the railway management staff to ensure the constant readiness of services and departments of the railways, rebuilding, repair and maintenance organizations, design and survey teams for recovery and to guide them in the performance of tasks. It includes:

- collection, synthesis and analysis of data on the consequences of natural disasters;
- development of solutions for the restoration of priority facilities and areas;
- setting goals for construction organizations and trusts for design and survey groups to perform priority work;
- clarification of tasks after approval of the decision to restore the railway, issuing orders for restoration and bringing them to the performers;
- monitoring the progress of restoration work;
- ensuring the interaction of organizations involved in the restoration;
- organization of commissioning of constructed facilities.

Situational center of the Railway Administration: organizes the collection, analysis and generalization of data on railway damage, sanitary and epidemiological situation, infection and flooding, restoration means of railway, construction and restoration organizations. On the basis of this data, proposals are prepared jointly with railway services and with the design and survey team on the sequence and timing of restoration of railway objects and directions; After that, the situational center provides the chief of the railway with generalized data on the consequences of the earthquake; Further, construction organizations consider documents on the organization and production of restoration work and, after coordination with the railway services, they are submitted for approval to the head of the railway.

Based on the assessment of the situation prevailing on the railway and received from the ground and airborne technical reconnaissance groups in the earthquake area, the railway chief decides to restore the priority railway facilities and directions.

The decision of the chief of the railway to restore the priority objects and directions of the railway includes: the operational situation, the current situation on the railway, directions in which the movement of trains is disturbed, destroyed objects, areas of infection, flooding; forces and means for restoration that are available on the railway, their deployment timing, recovery movement. The decision is drawn up by order of the chief of the iron.

In the order of the chief of the railway for restoration, the following tasks are indicated: performers, term, objects (nodes, bridges, tunnels), type of restoration; readiness of design documentation; forces and means; materials and structures allocated from the reserve.
Providing delivery of construction and restoration organizations; material and technical support for restoration work with materials and structures. The order of acceptance of the restored facilities into operation is indicated; the location of the situational control point of the railway, the procedure for reporting.

The main goal of railway management is to ensure, that the restoration of the railway will reinstate, the maximum efficiency of the use of forces, assets and railway infrastructure.

**Step 3. Situation awareness - evaluation – decision process.**

This is a classical management task evaluation of the available information and decision making including:

- situation awareness – realization of the damages size and forms, possible consequences, etc.
- using simulation methods for understanding the possible effects of the different management actions),
- evaluation and analysis of the results,
- selecting the applicable solutions for solving the identified problems from the set of possible solutions and choosing the solution that may and will be applied (for example, the bridge damage is detected, the set of possible solutions includes repairing, making a new part, building a temporary pontoon bridge, developing the roundabout way, and the applicable way is chosen, namely, through the realization of the availability of materials, technology, human resources).

In the mountains of Kazakhstan, during catastrophic earthquakes, giant landslides and seismogenic mudflows are possible, which can cause significant damage to the railway.

- **Mudflows**: There are 42 mudflow basins in the Almaty region, 147 settlements can be exposed to mudflow danger, including in Almaty (18%) with a total number of inhabitants of about 1.91 million people.
- **Landslides**: In the Almaty region, the area of landslide formation is about 28.6 thousand km squared, and possible landslides are 22.3 thousand km sq.
- **Infectious diseases**: In the period after the earthquake, activation of infectious diseases due to local and imported sources is possible.

In the territory of Almaty region, there are: 13 natural foci of plague; 182 points permanently dysfunctional for anthrax, also on the list of dangerous infections: typhoid fever, acute intestinal infections, viral hepatitis. Here, to ensure the survivability of the railway network and the continuity of traffic, bypass nodes are being prepared, duplicating bridge crossings, ferry crossings, connecting branches.

In case of a barrier on the bridge during the destruction of the railway (node, tunnel), to ensure the continuity of traffic, a decision is made to bypass (BP) or restore the railway.

The destruction of large hydroelectric dams and the dumping of huge masses of water in a short time can cause disastrous consequences. Railway embankments, bridges and stations may get damaged greatly. The destruction of such sections, in addition to the malfunction of the railways can lead to flooding of large areas of the terrain.

Emergency response and disaster recovery require significant investment in resources and adaptation. Thus, the assessment and adaptation of railway facilities and bridges to risks becomes an important issues.

This study considers railway junctions (stations) and bridges as a critical infrastructure and explores measures to protect stations facing natural or man-made disasters. Figure 36. and Figure 37. show possible ways to bypass railway nodes and bridges on the railway of the Republic of Kazakhstan.
Figure 36. Variants of outcomes of critical objects on the railway of the Republic of Kazakhstan a.) the Almaty node; b.) the Shu node; c.) the Arys node; d.) the bridge across the Ili river; e.) the bridge across the Irtysh river.
The BP is a set of devices that ensure the transportation of people and material goods bypassing the destroyed critical objects of railway transport.

One of the main elements of the power supply are loading and unloading stations located on the approaches to the destroyed facility. The required number of stations is determined by the calculations based on the volume, nature of transportation and the duration of the cargo operation.

BP specialization is carried out taking into account:
- rational use of automobile and pipeline transport;
- the minimum cost of motor resources when following trains from the unloading station to the loading station;
- the state of automotive approaches and station devices.

The station’s track development should ensure the fulfillment of a given amount of work on the passage, unloading and loading of trains.

The technology of operation of unloading and loading stations in a power supply depends on:
- specialization of stations;
- lengths of loading and unloading railways;
- a method of transferring goods from one mode of transport to another.

At the loading - unloading station, the following operations are performed:
- reception and departure of trains;
- technical and commercial inspection of cars;
- supply, selection, cleaning of cars;
- loading, unloading, delivery and acceptance of goods;
- execution of shipping documents.

It is advisable to supply fuel and lubricant trains by routes with homogeneous and dissimilar cargoes, but the pre-selected groups by their type of fuel. Fuel can be transferred according to the scheme of the tank - pipeline - tank or using intermediate tanks.

**Step 4. Further and broader evaluation**

Objectives of these tasks are the followings:
• getting information from the recent data (provided by the staff that arrived to the site of the damaged critical elements, or collected via distance measurement means, for example, by drones),
• using statistical methods for understanding and evaluating the possible secondary effects, collecting new data,
• getting data from the aftershock detection (or simulation of aftershocks by using the Monte-Carlo simulation)
• simulation of the possible processes including aftershock and secondary effects (that may reach the given zones after a couple of hours or even days – e.g. flood that can be simulated by using the CFD methods).

In modern conditions, new information technologies allow online access to information about destroyed railway transport facilities and at a considerable distance from the facility. Therefore, the use of drones to collect information will allow the possibility for quick decision making on the restoration of destroyed transport objects, and the use of the Mont-Carlo method, will allow the selection of the best option for recovering railroads by repeatedly modelling a large number of alternative solutions.

The exploration of objects (sections) of the railway that have been destroyed as a result of earthquakes is carried out in order to timely provide the management and design and survey teams of the railway, the heads of restoration works with the necessary data to develop design documentation, plan and conduct restoration work.

A general assessment of the destroyed objects, determination of the extent and boundaries of landslides, flooding of objects and the surrounding area is carried out by the civil defence intelligence of the iron ore departments with the subsequent transfer of the necessary information to the management of the road.

The main tasks of intelligence are:

• collection and study of reliable information on the nature and extent of destruction of railway facilities (nodes, bridges, tunnels, determination of the boundaries of landslides and fires);
• determination of the effects of breakthrough and flooding waves on railway facilities during the destruction of hydroelectric dam and reservoirs;
• on-site identification of possible options for restoration of facilities, estimated volumes and methods of production of works ensuring their implementation in the shortest possible time; identification of preserved or partially damaged structures and devices, as well as the availability of restoration of local materials;
• clarification of the presence and condition of roads for the transport of materials, structures and equipment;
• clarification of areas of possible location of construction and restoration organizations.

If necessary, technical intelligence teams are strengthened by specialists from comprehensive design and survey teams, divisions, departments and road services.

Teams of reconnaissance of objects of the railway consequences of the earthquake conduct:

• an examination of the destroyed objects and the surrounding areas;
• survey results and their proposals are recorded on diagrams or maps, which are timely transmitted to the head of the restoration work of the facility.

Intelligence materials for the restoration of the facility are submitted to the railway department in a short time.

When developing project documentation, specialists of the design and survey team use intelligence materials.
Railway intelligence data should be sufficient for the accelerated development of project documentation for the restoration of the facility, organization and production of works. In order to speed up the decision to restore, aerial reconnaissance of the railway is carried out using UAVs.

**Step 5. Making a higher level decision**

There are two major tasks to be solved during this step:

- getting information about the possible changes connected with objectives and prioritisation (for example, because of a flood or tsunami people have to be evacuated to another place),
- making a decision (this model deals with the decision related to technical / technological recovery of a railroad and railway systems, whereas evacuation of the people is a task managed by another sub-group of staff and managers).

The successful solution of the tasks of eliminating the consequences of earthquakes is associated with the solution of a whole range of tasks, the main of which are: continuous production, collection, study and analysis of environmental data; decision-making; bringing tasks to subordinates; planning; organization and maintenance of continuous interaction; comprehensive support of restoration work; preparation of forces and means for the restoration of the railway and their direct management; organization of control and assistance.

**Organization of restoration works:**

1) Restoration of the railway trackbed.
   a) the works on restoration of the railway trackbed include:
      - construction of the roadbed for destroyed nodes, tunnels, and other objects;
      - construction of railway roadbed on the way to bridges;
      - restoration of the destroyed roadbed on certain sections of the road.
   b) when constructing a railway roadbed on detours, the terms of restoration of objects as a whole should be limiting in terms of the volume of work and labour intensity.

In the railway excavation project, the following should be indicated:

- volumes of railway excavation works and conditions for their production;
- the necessary amount of equipment to carry out preparatory, basic and finishing work;
- the need for fuel and oils, the conditions for their storage, delivery and refuelling of equipment at the work sites;
- mode of operation at the facilities, maintenance of mechanization equipment.

2) Restoration of the upper structure of the railway:
   a) The system of the restoration of upper structure of the railway track includes:
      - laying and ballasting of the railway track on detours of nodes and tunnels and on approaches to the bridge;
      - laying and ballasting of the track on the same axis after the complete destruction of the railway track lattice;
      - laying of rails after their complete or partial destruction; repair of the railway track in order to eliminate individual damage;
      - clearing the railway from the rubble.
   b) Laying the upper structure of the railway track bypass is usually carried out on a wide front from two points towards or from one point in different directions.
The assembly of railway links of the sleeper-and-sleeper lattice is carried out at production bases or at linking bases.

On laying the upper structure of the railway track, tracklayers are used.

The ballasting of the railway track on the constructed bypasses is carried out after laying the upper structure of the railway track. Ballasted train tracks should be finished after running the trainload. Clearing the way from the rubble is an important measure in restoring train movement on the same axis.

The method of clearing is selected taking into account the volume and nature of the debris.

c) Work on the restoration of the upper structure of the railway track in sections is carried out, as a rule, by flow and, in some cases, integrated methods.

The flow method must be used when laying, ballasting and disassembling the railway track;

Mixed methods are used when restoring the destroyed railway track in small railway sections and at railway stations;

Complex methods - in cases when work is carried out by complex teams on the railway sections of the partially damaged railway tracks, when restoring switches, special tracks.

d) To restore the upper railway track, a project for the production of works is being developed.

This project indicates:

full volumes of preparatory, basic, auxiliary and finishing work on each site;

ways of organizing work and the procedure for their implementation;

the need for labour in the whole facility.

the required number of means of mechanization;

the required number of elements of the upper structure of the railway track and other materials and their terms for the railway sections of restoration work;

production technology for each type of destruction and work schedule for the site being restored.

3) Reconstruction of bridges and pipes

a) The structure of the restoration of bridges and pipes includes:

restoration of bridges on the previous axis;

the construction of small bridges and pipes on constructed bypasses; restoration of damaged bridges or small bridges and pipes.

b) Bridges and approaches to them on the restored bridge crossing are constructed as temporary or short-term.

c) A project for the production of works is being developed for the restoration of the bridge, which includes:

a calendar schedule of the works on the restoration of the bridge and work schedules for the work sites indicating the duration of their implementation and the need for forces and means for each work process as a whole;

schedules for the manufacture and receipt of structures and materials indicating delivery times and resource requirements;

construction site plan;

technological instructions and schemes for the production of basic and transport work;

schemes and procedures for the assembly and installation of spans; working drawings of auxiliary devices.

When developing a project for the production of works, it is necessary to use the available technological instructions, manuals and maps. In the work schedules of the work on
the sections, all work processes and operations, the sequence and methods for their implementation are indicated both for individual sections, and for the bridge as a whole.

4) Tunnel restoration

a) Tunnel restoration is carried out in the following ways:
   ✓ construction of a temporary detour;
   ✓ construction of a short-term detour for autotractor traction; opening the tunnel into a recess;
   ✓ restoration of the tunnel on the previous axis.
   ✓ The construction of a temporary bypass of the tunnel is carried out according to lightened technical conditions.

b) To restore the tunnel develop:
   ✓ during the construction of the bypass - the project of excavation and the project of laying the upper structure of the railway track;
   ✓ when restoring the tunnel to the previous design, work on getting rid of the blockage or opening the tunnel into a recess.

The project of works on driving blockages by a mining method or developing a tunnel into an excavation contains a tunnel diagram and a calendar schedule that indicates the amount of work, the required forces and funds for the implementation of preparatory, main and final works.

Step 6. Regular evaluation of reaching the objectives

There are three subtasks that require solutions.

• determination and evaluation of the indicators – that describes the status of the quick recovery process (reaching the operational level of the railroad and railway systems)
• development and evaluation of a combination of the indicators
• making a decision on further steps.

Reconstruction of the railways is a set of measures to restore the smooth movement of trains interrupted due to destruction, wrecks or accidents. It is often carried out by recovery trains equipped with powerful cranes, necessary equipment and materials.

By the nature of the work performed, the restoration of railways can also be short-term, temporary and capital.

Short-term restoration is carried out immediately after a crash or accident with maximum use of materials and local resources remaining during the destruction. It should provide an urgent restoration of train traffic, at least with reduced speeds, over a limited period of time. In this case, the simplest recovery methods and lightweight structures are used: damaged rails with simplified fastenings are stacked.

The temporary restoration of railways should ensure the uninterrupted and safe movement of trains and a given throughput for a relatively long period. In this case, it is allowed to lay shortened rails and a number of sleepers reduced against the norm per 1 km of track with a reduced thickness of the ballast layer under the sleepers.

Capital restoration of railways is carried out in compliance with the requirements and technical conditions. At the same time, it is envisaged not only to bring the production capacity and throughput of the railway to previously installed (or accepted), but also to reconstruct it and further develop it in accordance with modern requirements, taking into account the use of new technology.

Ways to restore the upper structure of a railway track are determined by the nature of the damage and the type of restoration.

As the experience of some countries show, the use of the following progressive technical means of restoring railways can significantly accelerate the opening of train traffic on railways during the period of recovery and repair after natural disasters:
• floating railway bridges NZHM-56 (Figure 38. a.));
• track renewal train RU-800S (Figure 38.b.));
• mobile platform machines(Figure 38. c.));
• powder hole drift ПД-3 and powder rall-breaker ПР-2, etc. (Figure 38.d.)).

To evacuate and provide emergency medical care to the injured and sick victims of earthquakes, it is proposed to use evacuation and sanitary trains, which will significantly increase the effectiveness of medical assistance to victims located at a considerable distance from hospitals.

For example, as of 2010 in Russia there are five mobile consultation and diagnostic centres based on railway trains: "Health", "Doctor Voino-Yasenetsky-Saint Luke", "Therapist Matvey Mudrov", "Academician Fyodor Uglov" and "Surgeon Nikolai Pirogov" (Википедия,
2016). Kazakhstan also has "Densaulyk" evacuation sanitary trains (Figure 39.). In 2019, the Densaulyk evacuation ambulance train cruised through 195 stations in Kazakhstan and provided assistance to about 60 thousand people living in villages (Новости Казахстана, 2019).

Figure 39. Evacuation sanitary train "Densaulyk» (Денсаулык жолы, 2019)

Approximate composition of the medical train:
- cars with medical offices and equipment - 5;
- a car equipped with a diesel generator for Autonomous power supply - 1;
- cars for accommodation and rest of medical staff - 4;
- restaurant car - 1;
- car-pharmacy - 1, can also attach up to 10 additional cars for patients.

3.3. Further works

Step 7. Long term planning

Further works deals with planning the long-term restoration by
- estimation and characterisation of the final damages, essential to apply long term recovery processes,
- determination of the objectives of the long term recovery processes
- (preliminary) planning of the long term recovery processes.

As part of the emergency management system, planning is the most important element that determines all the necessary actions in preparation for emergency situations, in the event of a threat and the occurrence of large-scale natural disasters, especially earthquakes.

The purpose of response plans is to create the conditions for the effective implementation of search, rescue, other urgent emergency, restoration work and activities aimed at saving lives, reducing the negative impact of natural disasters, social and material damage.

In accordance with current legislation, emergency management planning is carried out at the national, sectoral, local levels, as well as at the level of enterprises / organizations.

ASF emergency management plans determine the order of the responsible actions, measures that allow for an effective response to earthquakes, floods, floods, mudflows, landslides, natural fires, epidemics and epizootics.

Among the main plans is the "Action Plan of the Chairman of the Committee on Emergency Situations of the Republic of Kazakhstan on the organization of work in case of threat and the occurrence of a destructive earthquake.” This Plan includes the following items:
- assessment of the situation and notification of the population, all interested bodies about emergency situations;
- activation of communication systems, implementation of operational plans of the Emergency Committee, “Earthquake Action Plans”, “General Plan for the Elimination of Emergency Situations” of ministries and departments;
- the introduction of forces and means for emergency rescue operations;
collection of the Interdepartmental State Commission for the Prevention and Response of Emergencies;
• report to the head of the republic’s civil society - to the Prime Minister and the President of Kazakhstan;
• creation of reconnaissance groups, reconnaissance in the emergency zone;
• creation of a situational emergency map and assessment of the development of seismic situation;
• delivery and deployment of emergency rescue units to the emergency zone;
• military engagement;
• access to the Interstate Council for Emergencies with information on possible assistance;
• control over the deployment of forces and means;
• rescue and other urgent work;
• reception of victims and emergency medical care;
• organization of supplies of necessary material and technical resources;
• ensuring the safety and security of critical facilities in the emergency zone;
• fire fighting;
• registration of the evacuated population and communication with the media;
• organization of restoration and repair work;
• report to the leadership of the country on the activities undertaken.
• At the enterprise level, civil defence plans and plans for the elimination of the consequences of emergencies and natural disasters (earthquakes, floods, fires, etc.) are also being developed.

In addition to civil defence plans, emergency management, if necessary, is also carried out on the basis of the closed “Plan of interaction of the Emergency Committee with the Ministry of Defence, the Ministry of Internal Affairs, the National Security Committee and the National Guard of the Republic of Kazakhstan in the event of an emergency,” which prescribes the necessary coordinated actions, the volume of forces and means involved in specific cases.

The preparation of railway for liquidation of consequences from earthquakes (advance) should be carried out taking into account modern requirements for transport, the main of which are:
- the correspondence of the throughput and freight capabilities of the railroad with the given volumes of traffic;
- ensuring the high survivability of the transport system and the continuity of railway traffic;
- creation of an intermodal transport network for the integrated use of modes of transport.

The main goal is to ensure maximum efficiency in the use of forces, means and infrastructure of railway transport.

Classification and tasks of seismic forecasts

Seismological services are currently compiled for decision-making bodies of the Republic of Kazakhstan. Three types of forecast (Figure 40.):
- Long-term (2-10 years) - allocation of formation zones future foci of earthquakes.
- Medium-term (1-2 years) - forecast seismic degree danger zones identified by long-term forecast.
- Short-term (1-30 days) - forecast and assessment of parameters expected seismic events in zones identified by long-term and medium-term forecasts.
Figure 40. Long-term forecast areas preparation of strong earthquakes in the Almaty region

Early events are carried out in order to prepare the railway for work in case of emergencies of a natural and technogenic nature and consists in the organized transfer of forces and means of the railway to carry out restoration work and create conditions for restoring interrupted train traffic in the shortest possible time.

These include:

- Strengthening bandwidth and creating its reserves;
- the construction of new railway lines, bypasses of railway junctions, bypass lines of communication, approaches to places of flooding and the construction of temporary bridges and other facilities that ensure uninterrupted operation of railways;
- training of rehabilitation and maintenance organizations;
- accumulation in warehouses of recovery materials, equipment and property;
- organization and testing of machinery mechanisms, equipment laid in storage warehouses;
- preparation of the institutes for conducting survey and design work at railway facilities.
- development of design and technical documentation, providing a reduction in the lead time for survey design decision making;
- training management and engineering staff on the ability to conduct restoration work at a fast pace and provide reliable recovery management.

Early events are developed by railway chiefs.

Planning for the restoration of railways in the event of earthquakes is carried out in order to ensure comprehensive and complete preparation of railway organizations for the restoration of destroyed facilities and the resumption of interrupted train traffic in the shortest possible time. It includes:

- forecasting the likely destruction, infection and flooding of railway facilities and sections; forecasting probable personnel losses;
- material and technical means;
- forecasting the volume of work of the first stage and the need for funds for their implementation;
- determination of early events, their sequence and deadlines;
- the definition of the organization of organizations for railway facilities for restoration and the definition of tasks for construction and restoration organizations;
- determination of the main functions and responsibilities of governing bodies.

Mitigation of the consequences of earthquakes may include: reconnaissance of areas of destruction, rescue, medical, evacuation and anti-epidemic measures; clearing and restoration of railways, roads; timely withdrawal of the affected population from hazardous areas of destruction, infection, flooding and fires; restoration of the moral and psychological state of the affected population; their special treatment, disinfection of structures, equipment, materials, terrain and roads.

The calculations of the forces and means involved in eliminating the consequences of earthquakes in the Republic of Kazakhstan are established by the action plans for emergency response of global and regional scales of the authorized body in the field of civil protection.

### 3.4. Drone applications for supporting the disaster response management of the transport system

Drones are new unmanned aerial vehicles. They can carry many different types of sensors, optical, infrared cameras. They do not need specially equipped sites for their work. They can be autonomous or remotely controlled, and measurement data in the observed areas can be transmitted from the drones over the Internet and over long distances. Using unmanned applications to support strategic transport response management will help speed up the rescue of the affected population and identify damage to the transport system.

*Time scale of drone activity supporting disaster management:*

- before the occurrence of a disaster;
- the period immediately after the occurrence of a disaster;
- the period after the primary disaster elimination activity.

*Figure 41.* shows a structured drone application.

![Structured drone application](Á. Restás, A. Zhaulybayev, E. Shumatov, K.Akshulakov, 2020)

Using a drone, you can monitor the situation on the railway line in real time in automatic mode, perform operational reconnaissance from the scene of an accident or disaster on a road facility, thereby allowing operators and managers to make management decisions in the shortest possible time.

*Figure 42.* shows a simple structure of a UAV mission during earthquake response on a railway.
The main tasks for using unmanned aerial vehicles on the railway:
- Firstly, UAVs can monitor railway tracks, bridges, tunnels and other objects.
- The second task may be to monitor emergency incidents when a UAV, as part of a repair group or an Emergencies Ministry group, arrives at the scene. In this case, multicoaters are more suitable. Videos and photos can be transmitted in real time to all interested officials - rescuers, repairmen and the emergency response headquarters.
- The third point of using UAVs on the railway could be to monitor the movement of high-speed trains in real time.

The most actively developing direction of the use of UAVs in the activities of railway, at present, has become the solution of the second problem - the use of UAVs to help assess the scale of emergency situations, which leads to the need of improvement and development of the technological base for creating UAVs. In addition to the visible range of camera, the installation of a thermal range camera for monitoring fires can be an option for upgrading existing UAVs on the market. Also stabilization of video protocols is required so that all participants in the events can access video information from a drone with a camera. The kit itself must be very easy to operate, brought into working condition from the stowed position in a short time, and have a margin of flight duration. With the help of drones, you can get a lot of data about the state of the railway track, including its geometry, which is important for high-speed trains.

Below I show figure 43, with elements of the earth bed and made a table 35 about the possible destruction of the railroad bed after earthquakes, which can be detected using the UAV.
Figure 43.  Elements of railway subgrade: 1 - borrow; 2 - line; 3 - subsoil; 4 - slope; 5 - terrace; 6 - longitudinal drainage ditch; 7 - slope; 8- zero place; 9 - pit; 10 - shoulder; 11 - ditch; 12 - subgrade; 13 - section; 14 - banquette cut; 15 - cut; 16 - catchwater drain (РЖД, 2000).

Table 8.  Compilation of damage types (РЖД, 2000)

<table>
<thead>
<tr>
<th>1) Subgrade</th>
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<td>common groove under several sleepers</td>
</tr>
<tr>
<td>pocket - having one or more outgrowths of pockets</td>
</tr>
<tr>
<td>Thermochrest depression</td>
</tr>
<tr>
<td>distortion of the position of the rail threads in the longitudinal and transverse profiles</td>
</tr>
<tr>
<td>rail track distortion in the longitudinal profile above gas pipelines</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2) embankment slope railway</th>
</tr>
</thead>
<tbody>
<tr>
<td>surface disturbance of slopes by water</td>
</tr>
<tr>
<td>Collapse of steep cut slopes in loess soils</td>
</tr>
<tr>
<td>a) cutting b) embankment</td>
</tr>
<tr>
<td>Erosion of the slopes of dam and offset</td>
</tr>
<tr>
<td>displacement of the topsoil</td>
</tr>
<tr>
<td>Slides of the slope parts of the embankment over the heating main crossing it</td>
</tr>
<tr>
<td>stumping of loose sediments and rocks</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3) scree creep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creep of embankment slopes</td>
</tr>
<tr>
<td>Slides of the slope parts of the embankment over the heating main crossing it</td>
</tr>
</tbody>
</table>
### 4) roadway

- Spreading of the embankment slopes
- Embankment shift
- Deformation of the subgrade
- Embankment offset

### 5) support

- Destruction of sloping parts of the roadbed
- Embankment subidence
- Deformed embankment base
- Failures of embankments in peat bogs (silt deposits)

### 6) damage to the subgrade in the places of its interaction with foreign structures

- Subgrade settlement over pipe intersections
- Violation of surface water diversion at passenger platforms and loading and unloading areas
- Damage to the subgrade in places where cables are laid
- Subgrade subsidence over mines
As you can see, with the help of drones, you can get a lot of data: about the state of the railway track, including its geometry, which is important for the safety of train traffic.

3.5. Simulation methodology results

A simulation program was realised in Matlab environment following the recommended recovery management. This simulation is based on the active and adaptive methodology and may improve the traditionally applied response (generally disaster) management. The methodology had been developed specially to the response to damage of railway by earthquake. As it was defined, it uses recurring cycles of the zero + six + one steps, clouding semi empirical situation awareness – evaluation – decision making between each steps. The decisions between the steps is supported by the discussed sub-models employing different theoretical, semi-practical calculations and simulations.

A special leading or driving indicator of relative unused track length was introduced.
The structure of the response management and recommended management methodology applies available historical data about railway damages and fast recovery, followed by experts’ recommendations advising possible decisions in different simulated situations, uses simulation models employing approximation of the relative unusable track length. Then it changes the process by a Markov chain, that was adapted to the applied decision at each step and includes a Monte-Carlo simulation of the possible occurrence of the aftershocks (and secondary effects).
Figure 44 demonstrates the possible use of the developed management concept. As it can be seen, the first cycle might be repeated every step, while the second one depends on the available data after 3 – 5 steps. The objective of quick recovery is to return the railroad and the railway system to the operational level. Therefore, this part of the recovery can be finished after 2–3 days. In case of having a long-term secondary effect, for example a destroyed river dam, the quick recovery time may increase to 6–10 days. The complete recovery of the railroad and railway system may require 1–3 years.

Generally, the developed active adaptive response management to earthquake damage opens the way for further developments. The most interesting and important problem is – how the decision-making can be supported. There are several ways:

- starting from regular training of the staff,
- collecting the available information for improving the methodology and estimating the approximation constants, tuning the parameters,
- possible automation of the division making by implementing the methods of soft computing, as fuzzy logic, machine learning, etc.

Because of a very large sensitivity to the features and characteristics of the real event places and large uncertainties of estimable parameters, the artificial intelligence may support the further additivity of the methodology.

### 4. Testing, concept verification and validation of the developed model

#### 4.1. Simulation, model parameterization and testing

Simulation methodology was conceptually developed in a Matlab environment. It is a rather complex pack that uses different models, available software that needs further investigations, and adaption to the existing situations.

The simulation is based on the structure and tasks shown in Figure 45.

1. Task: Preliminary studies – that include definition of the problems, identification and evaluation of the possible methods for solving the problems, studies that use the selected supporting methods, software (a series of which had been cited by this thesis).
Figure 45. The developed simulation method for testing and concept verification, validation

2. Task: Hazard assessment – uses the historical data and results of the preliminary studies and harmonizes with preparedness; namely with predefined requirements of safety and security, improvements of the systems elements as trains, tracks, infrastructural elements, etc. by implementing the available safety technologies and possible monitoring of the system condition and occurring the events, earthquakes.

3. Task: Parameterisation - definition of the inputs, the required parameters for starting the simulation, i.e. response management. This task might be solved by using the databank and developed competences, knowledge, practices in managing with earthquake disasters. The inputs and required parameters are partly developed from monitoring and warning signals.

4. Task: Realization of the simulation - is developed and introduced by the sub-chapter 3.1. and shown in Figure 31. The concept of the response management of the railway to the earthquake disaster widely uses the experts’ evaluation of the available information.

5. Task: Post-event evaluation (of the results) – used for improving the historical data collection, data bank and preparedness.

As it can be understood from the figure 44. there are two major feature of this simulation technology:

- using a large set of methods, models and software selected from the set of methods according to the real situation;
- using the experts’ knowledge for adapting the methodology to the real situations.

These aspects are introduced by the following major problems of the disaster management that were identified:

- a lack in information about the potential hazards because of the complexity of the effects caused by earthquakes depending on the ground feature, random aftershock, secondary effects, etc.;
- there are no uniform or standard methods of risk analysis namely the interactions of the major earthquake and secondary effects, damage of the partly repaired system caused by aftershocks, and secondary effects;
- the methods for monitoring, prediction or warning of earthquakes are not fully applicable, even for the warning systems developed and applied to the fast trains;
- there is no simple and understandable information about the size of the earthquakes and (more importantly) about the possible aftershocks and secondary events. This information is crucial for reducing the time of evacuation, saving the people and goods;
- lack of education, training and evaluation of emergency situations (there is a wide system established for labour safety training, but it is poorly organized and does not properly working. It has been detected that, by using such methodology, common people will not able to evaluate the risk in disaster situation);
- difficulties in communication systems (the established system is not working satisfactorily in emergency situation, for example the lines and mobile phones are sometimes muted during floods);
- lack of the technical support (which is good enough for handling the accidents, even major accidents, but not really enough for handling the common accidents or disasters, since the regional centres only have a limited number of rescue vehicles, and very few personal safety clothes, personal devices for measuring, communication and response);
- difficulties in alarm and secession systems (in our practice, the time of cession after alarm is more important than procession with correct information about the situation, since the
territory should be defended, protected from other hazards, correct technical supports should be taken, etc.;

- there is no real decision support (technical support is acceptable, but information and communication system between the headquarter and regional centres of emergency agencies is not good enough, and they do not have any real time data-collection, data-processing. There is no any simulation software for analysing the effects of actions, meaning there is no any decision support software);
- lack of trained managers (there are no well-trained and experienced managers who can manage major accidents or disasters well, which is an important aspect in the situations described by emergency plans);
- there is no real decentralized decision system (the commander of response has limited possibilities to make decisions associated with other agencies, services, etc., however this might be caused by the lack of well-trained managers),
- there is no real plan for development (of technical, economic or social supports).

The required inputs and parameters must be defined after decision on the models, method intended to apply, and during the major cycles (that is defined in our simulations as every 6 minutes (0.1 hour)).

The host department of the author of this thesis, the Department of Aeronautics, Naval Architecture and Railway Vehicles at Budapest University of Technology and Economics deals with the situation awareness, evaluation and decision making of this long term research program. Throughout the working process well-known conventional model of Endsley (Endsley M. R.; Rodgers M. D., 2016) was improved by the current researchers, including the “Present Situation”, total load systems, as well as extending the “Task/System Factors” and “Individual Factors” (Figure 46).

Figure 46. The Adapted situation awareness model to the highly automated managing systems (Jankovics I.; Kale U., 2019), (Kale U., 2019)
According to the developed system, the individual human factors, namely skills, competence depending on the ability, knowledge, practice (tacit knowledge), training and mental condition are very important and represent real novelty of the developed management system that required further studies.

4.2. **Concept verification and validation**

The development of the concept, systems, models, etc. must be completed by verification and validation. Verification is needed to make sure that the examined model, the simulation, the developed software, system, etc. works appropriately and does what it is supposed to do, considering the conditions, standards, and so on. Verification proves that the examined model/system does not disregard any specifications and/or regulations. Developing a system requires frequent or continual verification. By using more simple definition, verification is mandatory to verify the completed system, product, which means that the regulation has been considered all the time. Verification proves that the examined model, the simulation, the developed software, system, etc. reflects reality and works as intended. Therefore, this is more than just a verification. Generally, the verification means the system works as intended, while validation demonstrates that the system works as it is supposed to in reality.

Because of the limited time and financial support for making a thesis, the developing concept can only be verified and validated.

After detailed investigation of the possible verification and validation, two possible ways were defined: (i) testing the concept in simulations and (ii) collecting the opinions of the experts by discussing the simulation results.

According to the first way, different historical data was used for checking different sub-models. Figure 47 – 50 shows results of such sub-model tests.

The developed earthquake response is based on

- objective measurements and realistic simulation of damages;
- methods of rapid assessment of the actual damages and measuring or simulating prediction of reaching the operational levels of the critical objects;
- models of using the available rescue and response technology and resources in an optimal way.

The developed response methodology may give information for all these tasks.

Figure 47. demonstrates the applicability of drones/UAVs to estimate and evaluate the earthquake damage to railway systems. As it can be seen, there are four approaches that can be used:

- simple visualisation
- simple geometric measurements (photogrammetry),
- using special image processing and measurements (infrared, synthetic aperture radars, lidar, etc.),
- using methods of soft processing (deep learning, machine learning, etc.).

Figure 48. shows how simple methods can be useful in response management. There is a segment of a railroad by bridges and tunnel. Table 9. introduces a special structural matrix of this sub-system. The condition of the system is given by one or zero, and depending on the given item it can either used, used with limitation or not used at all. The colours of the sub-parts operability depict the usability of the part by green, possible usability of the sub-part by yellow, reparability of the sub-part in the span of a week - one month by red, when the repair is required for more than one month as blue and unrepairable by black. The table contains the required
time, work in man-hours and any other comments like needs in a specific machinery, or huge financial support, etc.

Figure 47. Use of drones to estimation of railroad damage caused by earthquakes, a.) visualisation (Sokaoerial, 2020), b.) photogrammetry (Kromer, 2015), c.) lidar and (Gislounge, 2015)d.) deep learning (Institute, 2017)

Figure 48. Segment of a railroad

Table 9. Structural and repair requirements matrix of the rail segment shown in Figure 48

<table>
<thead>
<tr>
<th>State condition</th>
<th>S₁</th>
<th>S₂</th>
<th>S₃</th>
<th>S₄</th>
<th>S₅</th>
<th>S₆</th>
<th>S₇</th>
<th>S₈</th>
<th>S₉</th>
<th>S₁₀</th>
<th>S₁₁</th>
<th>S₁₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average time of repair</td>
<td>0</td>
<td>0</td>
<td>34</td>
<td>6</td>
<td>107</td>
<td>978</td>
<td>486</td>
<td>0</td>
<td>122</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Average work in man-hours</td>
<td>0</td>
<td>0</td>
<td>276</td>
<td>74</td>
<td>1642</td>
<td>10860</td>
<td>5100</td>
<td>0</td>
<td>1440</td>
<td>24</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Comments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Possible passing way 1.</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Possible passing way 2.</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Possible passing way 3.</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>
Possible passing way 3.  

Table 9. shows the possible operability of the given sub-system of the railroad by multiplication of the state condition values of the items included into the possible way of passing.

The next special aspect that has been studied is the possible modelling of the aftershocks prediction. As it was discussed earlier, the aftershocks are a large series of earthquakes smaller than the main earthquake. It can be modelled by using the Monte – Carlo approach. At each step of the cycle, two random values are generated, for predicting the possible occurrence of the aftershock by using the empiric distribution of the earthquakes like shown by Figure 30. First random value defines the size of earthquake and the second one calculates the probability of its existence. If the earthquake can occur (at a given time, the probability of its occurrence is less than the maximum value defined by Figure 30.), then its location can be generated by using another three random detections of the latitude, longitude and probability and using the ellipsis of distribution of the aftershock.

The practical studies show that, the zone of occurrence of aftershocks can be approximated by an ellipse. For example, ellipse shown in Figure 49.a contains approximately 90% of the plotted events. (Christophersen & Smith, 2000). Such distribution is recommended to approximate using bivariate normal distribution (Balakrishna & Lai, 2009). applicability of which is demonstrated by Figure 49.b.

Figure 49. calls attention on a special distribution of probabilistic density of occurrence of aftershocks in form of a 4D model. This means, the distribution depends on time (aftershock), intensity (earthquake module) and 2 dimensions of land (space). As usually, the aftershock distributions are also available in two-dimensional forms depending on time. (Guo & Ogata, 1997), (Silacheva, Kulbayeva, & Kravchenko, Probabilistic seismic hazard assessment of Kazakhstan and Almaty city in peak ground accelerations, 2018) (Rehman, Qadri, Ali, Al, & Ahmed, 2016).

For short-term prediction of the aftershocks a Monte Carlo simulation (Felzer, Becker, Abercrombie, Ekström, & Rice, 2002) is suggested to apply. The developed methodology uses two types of aftershock distributions, parameters of which are estimated from aftershock records. First one defines the probability and magnitude of occurred aftershocks depending on the time (Figure 30.). It might be drawn down by using the records, semi-empirical or semi-hypothetical approaches. The second one is the bivariate normal distribution of the location of appearing aftershocks (Figure 49. b.).

During the Monte Carlo simulation, 4 random values might be used in each cycle. First two defines the magnitude and probability of occurrence of aftershocks at given time (step). If the probability of occurrence is less than maximum defined for given time and magnitude (Figure 30.), then another two random values generated may identify the location of the predicted aftershock (Figure 49.b.)

This methodology takes into account only the predicted aftershocks with magnitude of 4 or greater.

Effects of an aftershock generated in simulation at the given k time step might be estimated by the same ways as effects caused by earthquakes. As usually, the aftershocks increase the relatively unusable track length.
Figure 49. Typical ellipse of aftershock distribution a.) aftershocks following the Mw = 9.2, Alaskan (1964) earthquake (epicentres of 243 earthquakes larger than magnitude 5.0 within 1103 km of the main shock and 10 months after the main shock are plotted (Christophersen & Smith, 2000)), b.) bivariate normal distribution approximating the aftershocks (Alaskan earthquake, top ellipsis of the simulated distribution; bottom three dimensional picture of the estimated bivariate normal)

As it can be seen, the Markov models are used for different purposes. Figure 50. introduces some results according to the use of Markov decision process, which are based on the simulation of restoration of critical elements of the railway system.

Figure 50. Markov process Organizing the decision process in a graphic table for the damage and undamaged states with the evolution of the mileage since last turning Wheel pairs (Braga, 2017)

The second way, collecting the opinion of expert, has been realised on three different levels. Discussions and meetings were organized with the representatives of

i. the researches on the study and investigation of the seismic effects, occurring the earthquakes and estimation of the size of damage from earthquakes,

ii. experts who had practice in managing the disasters, especially earthquakes, and
iii. specialists in operation, repairs and development of the system elements, like rail tracks, infrastructures such as bridges, tunnels, and other required technologies like the use of drones during disaster management

The studies were made by using quality analysis, that was transfer into the five merit containing 0 – 5 values. Zero means the presented managing system is unusable and 5 is well applicable. Finally, the results might be summarised as following:

- researchers concluded that, the developed methodology, still may not be applied to early warning of the earthquakes and aftershocks, while the size of damages and secondary effects might be predicted partially – the merit is about 3.8 – 4.0;
- managers, having large real life practice, evaluated the presented methodology as very useful for supporting their work, but they think that it would be problematic to recruit the required technical and human supports – their merit reaches 4.6 – 4.8;
- the opinion of the specialist differed a lot depending on their professions, as developer and designer, who usually apply the defined requirements, valued the method highly. The operators and people working on repair of the system, however, did not have such high opinions, while the experts working with new technologies, like image processing, drones, development and application of the micro sensors, etc. were rather optimistic – their merits were distributed between 4.2 and 4.7.

This part must be measured and corrected after the workshop and after different discussion, you may have.

4.3. Evaluation of the results

Several other simulations were realised based on the Figure 31. and 45. As it can be seen (Figure 51. and 52.) the simulations show that, the methodology might be used but it really must be used with continuous situation awareness – evaluation and decision on the model parameterization. Figure 51. demonstrates that the simulation results depend highly on the parameterization of the occurring aftershock, secondary effects, etc.

![Figure 51](image_url)

Figure 51. Simulation of a response management, a.) probabilities of being in the one of the 22 states, b.) changes in relative unusable track length (1.- main earthquake, 2.- aftershock, 3.- UAV information, 4.- flood, 5.- aftershock, 6.- new information about the flood)

Figure 52 shows interesting results of the percentage of people that might be evacuated by the railway comparing to the total that are waiting for evacuation by railway (the results are theoretical and show only the possible amount of people that could be evacuated, not the exact number).
Another important requirement might be defined as minimum technical and human support required.

The first one, the required technical preparedness must be defined depending on the available infrastructure, strategic development plants and real site conditions. For example, after examining the conditions of the infrastructure, studying the possible secondary effects, etc.

According to the possible improvement of the disaster preparedness and response system for Kazakhstan, the requirements in major, new technical elements might be defined as a very short and simplified list (Table 10.).

Table 10. New technical elements, required for improving the Kazakhstan Earthquake preparedness and response management (only some examples)

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>preparedness of the railway system</td>
<td></td>
<td>sensor integration into the bridges, tunnels, operation of drones in area control</td>
</tr>
<tr>
<td>1.1</td>
<td>regulation</td>
<td>new, improved regulation on the requirements in monitoring systems</td>
<td>T25 High Speed Shaft Style Rotary Torque Transducer; SSM or SSM2 Sealed S-Type Load Cell; LBM Compression Load Button Load Cell; MB Miniature Beam Load Cell; 1000 Fatigue-Rated LowProfile® Load Cell; 1200 Standard Precision LowProfile® Load Cell</td>
</tr>
<tr>
<td>1.2</td>
<td>sensors</td>
<td>different sensors types</td>
<td>WTS-AM-1E Acquisition Module.</td>
</tr>
<tr>
<td>1.3</td>
<td>data collection system</td>
<td>Laptop with Solar Panel supplied WTS Software; WTS-AM-1E Acquisition Module and Laptop Computer are also connected to a Solar Panel Backup System to ensure continuous operation during power outages</td>
<td>WTS-AM-1E Acquisition Module.</td>
</tr>
<tr>
<td>1.4</td>
<td>data processing</td>
<td>Force is measured by Load Pins and the measurements are transmitted to the WTS-AM-</td>
<td></td>
</tr>
<tr>
<td>1.5.</td>
<td>PC</td>
<td>PC computer with supplied WTS Software.</td>
<td>WTS Software</td>
</tr>
<tr>
<td>1.6.</td>
<td>Solar Panel</td>
<td>High Efficiency; high Reliability; low Hot-spot risk; Excellent loading capability.</td>
<td>GPNE-S72/FNH 390-410W</td>
</tr>
</tbody>
</table>

2. surveillance, control

2.1. drones | • Number of motors - at least 6 electric motors.  
• Propellers - must be made of high-tech materials.  
• Self-diagnosis of the device before the start of the flight and during the flight  
• Maximum horizontal flight speed - at least 10 m/s  
• The maximum duration of a flight with a payload of at least 3 kg is at least 40 minutes using a spare battery resource.  
• Battery at least 16,000 mAh.  
• UAV size (excluding propellers) - not more than 1800 mm in diameter  
• Maximum payload mass of at least 5 kg. | Large unmanned aerial vehicle with ground control system |

2.2. UAV ground control station | • The ground-based control system must ensure the change of the flight mission, the forced return of the UAV to the landing point.  
Modes of operation of the ground control system:  
• Flight planning mode;  
• flight mode;  
• Flight completion mode. | UAV ground control station "BLASKOR" |

2.3. vehicles | The control centre provides the autonomous deployment and operation of 2 unmanned aerial vehicles of the helicopter type, the reception and transmission of video from UAVs to a stationary communication centre. | Volkswagen Crafter all-wheel drive base |

2.4. mobile laboratories | mobile laboratories for biological control | mobile RFB field laboratory IMFL (Independent Mobile Field Laboratory) is mounted on two devices with a high degree of efficiency IVECO 6x6 and provides detection and exposure to chemical, radioactive and biological agents by analysing various matrices |

3. machines for response
The human resources depend on the managing system and structure establishing. Figure 53 shows one possible and recommended structure of management.

![Management and organisational structure for developed response system](image-url)
As it shown the response management is lead by a strategic manager, developing, planning and using the sources of the disaster response agency or organisation. The response management keeps connections with the stakeholders (including the government, agency, economy leaders, and society representatives) and especially with media and policy makers.

The tactical manager acts as an executive manager, collecting the information on control of the required extra surveillance, measurements, making decision on active control.

The operations manager provides access to the work of all technical, human (knowledge) and financial sources.

There is a special manager that deals with safety, security and defence aspects.

The program must be finalised depending on the possible levels of hazards detected, population, industrial density, etc. The final program must include special training system and recruitment of a special human resource for reservists.

4.4. Applicability of the developed methodology

To implement the theme proposed in the thesis on modelling the restoration of the railway system after earthquakes, a feasibility study will be required. A feasibility study is being prepared to determine the best organizational, technical and economic solutions for creating a monitoring system for the main elements of the railway (bridges, tunnels, etc.) designed to support the railway system in case of natural disasters.

In Kazakhstan, a feasibility study is developed in accordance with the requirements of the Minister of Economic Development and Trade of the Republic of Kazakhstan, dated August 19, 2010 No. 6402 (Tengrinews, 2019) and contains the following mandatory sections:

- project passport;
- introduction;
- institutional section;
- marketing section;
- technical and technological section;
- environmental section;
- financial section;
- socio-economic section;
- risk assessment and distribution;
- conclusions on the project;
- applications (if necessary).

In this section of the dissertation, a preliminary feasible study on the implementation of the dissertation results is prepared.

The passport:

- Preliminary name of the project: Modelling the restoration of the railway system after an earthquake.
- Place of project implementation: Republic of Kazakhstan.
- Objective of the project:
  - The implementation of the project provides the Republic of Kazakhstan with:
    - Study of the main objects of railway transport infrastructure to support the management of the railway system after earthquakes and other natural and man-made disasters.
    - Creation of an information basis for the development of high-tech industries.
- Project Objectives:
  - Creation of a ground-based complex for managing and monitoring the railway system in case of earthquakes;
- Creation of a mobile complex for managing and monitoring the railway system in case of earthquakes;
- Creating a ground-based measuring system - a network of sensors for measuring the state of the railway system;
- Testing the system for measuring the state of railway infrastructure;
- Integration of the system into the State Information Analytical System of the Republic of Kazakhstan.
- Improving the speed of decision-making and the effectiveness of decisions in government bodies and organizations related to emergency situations.

- Project scope: Railway system:
  - UAVs.
  - UAV ground control centres.
  - Mobile UAV control centres.
- Ground measuring system - a network of ground sensors on the main elements of the railway infrastructure.
- Project implementation period: 12 months.
- Object operation period: not limited.

The project cost is $178,220,726 (Table 11.)

<table>
<thead>
<tr>
<th>Item Nr</th>
<th>Description</th>
<th>Unit</th>
<th>Quantity</th>
<th>Unit Price $</th>
<th>Amount $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bill No.1: Preliminary and General</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>Contractual requirements</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1.1</td>
<td>Performance Bond</td>
<td>sum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1.2</td>
<td>Insurances in accordance of Conditions of Contract</td>
<td>sum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>Specified requirements</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.1</td>
<td>Survey of the Site to establish sensors</td>
<td>sum</td>
<td>340946</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.2</td>
<td>Survey and all other related survey work</td>
<td>sum</td>
<td>120000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.3</td>
<td>Design Management, Expediting and Coordination</td>
<td>sum</td>
<td>600000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.4</td>
<td>Training &amp; training and support.</td>
<td>sum</td>
<td>90000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.5</td>
<td>Compliance with Environmental Protection Requirements</td>
<td>sum</td>
<td>100000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.6</td>
<td>Operation and Maintenance Manuals</td>
<td>sum</td>
<td>60000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bill No.2: Procurement &amp; Supply of Materials &amp; Spares machines &amp; mechanisms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.1 Materials, machines and mechanisms

<table>
<thead>
<tr>
<th>Item</th>
<th>Code</th>
<th>Quantity</th>
<th>Unit</th>
<th>Rate</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP Load Pin.</td>
<td>nr</td>
<td>15000</td>
<td></td>
<td>240</td>
<td>3600000</td>
</tr>
<tr>
<td>WTS-AM-1E Acquisition Module.</td>
<td>nr</td>
<td>1500</td>
<td></td>
<td>150</td>
<td>225000</td>
</tr>
<tr>
<td>WTS-BS-4 Industrial Base Station.</td>
<td>nr</td>
<td>1500</td>
<td></td>
<td>460</td>
<td>690000</td>
</tr>
<tr>
<td>Customer’s Data Acquisition System.</td>
<td>nr</td>
<td>52</td>
<td></td>
<td>700</td>
<td>78000</td>
</tr>
<tr>
<td>PC computer with supplied WTS Software.</td>
<td>nr</td>
<td>52</td>
<td></td>
<td>900</td>
<td>46800</td>
</tr>
<tr>
<td>Solar Panel.</td>
<td>nr</td>
<td>15000</td>
<td></td>
<td>200</td>
<td>3000000</td>
</tr>
</tbody>
</table>

2.2 Machines and mechanisms

| Item                                                               | Code | Quantity | Unit | Rate | Total   |
|                                                                   | nr   | 52       |      | 4300 | 223600  |
| Unmanned aerial vehicle with ground control system                | nr   | 52       |      | 4165 | 216580  |
| UAV ground control station                                         | nr   | 52       |      | 41000| 88528000|

Bill No. 3: Construction work

<table>
<thead>
<tr>
<th>Item</th>
<th>Code</th>
<th>Quantity</th>
<th>Unit</th>
<th>Rate</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mounting sensors</td>
<td>nr</td>
<td>15000</td>
<td></td>
<td>150</td>
<td>2250000</td>
</tr>
<tr>
<td>Installation of solar panels</td>
<td>nr</td>
<td>15000</td>
<td></td>
<td>150</td>
<td>2250000</td>
</tr>
<tr>
<td>Cabling</td>
<td>m</td>
<td>750000</td>
<td></td>
<td>100</td>
<td>75000000</td>
</tr>
<tr>
<td>Installation of Industrial Base Station</td>
<td>nr</td>
<td>1500</td>
<td></td>
<td>260</td>
<td>390000</td>
</tr>
<tr>
<td>Commissioning works</td>
<td>sum</td>
<td></td>
<td></td>
<td>11800</td>
<td></td>
</tr>
<tr>
<td>Test</td>
<td>sum</td>
<td></td>
<td></td>
<td>12000</td>
<td></td>
</tr>
</tbody>
</table>

Bill No. 4: Dayworks & Provisional Sums

<table>
<thead>
<tr>
<th>Item</th>
<th>Code</th>
<th>Quantity</th>
<th>Unit</th>
<th>Rate</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schedule of Daywork Rates</td>
<td>hour</td>
<td>500</td>
<td></td>
<td>150</td>
<td>75000</td>
</tr>
<tr>
<td>Labour</td>
<td>hour</td>
<td>500</td>
<td></td>
<td>155</td>
<td>77500</td>
</tr>
<tr>
<td>Driver</td>
<td>hour</td>
<td>500</td>
<td></td>
<td>155</td>
<td>77500</td>
</tr>
<tr>
<td>Skilled Labourer</td>
<td>hour</td>
<td>1000</td>
<td></td>
<td>155</td>
<td>155000</td>
</tr>
<tr>
<td>Room rental for control room ground</td>
<td>month</td>
<td>12</td>
<td></td>
<td>250</td>
<td>3000</td>
</tr>
</tbody>
</table>

Total sum: 178220726

The main beneficiaries in the Republic of Kazakhstan:

Government structures:
- Ministry of Transport and Communications
- Ministry of Education and Science
- Ministry of Emergencies
- Ministry of Natural Resources Protection
- Ministry of Economics and Budget Planning
- Ministry of Industry and Infrastructure Development

The main beneficiaries in the Republic of Kazakhstan:

Consumers of the project results:

Potential users of the research are scientific organizations of Kazakhstan and the railway of the Republic of Kazakhstan.
Estimated Sources of Funding: State budget of the Republic of Kazakhstan.
The role of the project in the development of the economy of the Republic of Kazakhstan:
The implementation of the project provides for the Republic of Kazakhstan:
Creation of an information basis for the development of high-tech industries.
Improving the speed of decision-making and the effectiveness of the decisions of government bodies.
Improving the structure of employment by increasing the demand for specialists in the field of high technology.
The implementation of the project will provide:
Creation of seismic monitoring of railway facilities of Kazakhstan.
Allows the raise of the quality level of scientific research and development methods for monitoring and assessing seismic hazard to reduce the consequences of emergency situations on the railway.
One of the goals of the project is to increase the efficiency of managerial activities of state bodies in solving the problems of control and balanced sustainable development of sectors of the economy and regions of the Republic through the introduction of new information technologies.
In particular, as a result of the project, the following is achieved:
Preparation of informational support for decision-making on measures to protect the population from natural disasters, on emergency response, on measures to protect the environment.
Relevance:
- The number of strong earthquakes on Earth since 1992 has been increasing significantly and there is no downward trend.
- Over the past 50 years, about 1 million people have died from earthquakes all over the world, and the damage from them is hundreds of billions of dollars.
Recent major earthquakes and casualties:
- Ashgabat (1948) \( (M = 8) \) 50 thousand people died;
- Spitak (1987) \( (M = 7.8) \) 25 thousand people died;
- Tanshan (China) \( (M = 8.2) \) 183 thousand people died;
- Indonesia (2004) \( (M = 9) \), killing 283 thousand people;
- Pakistan (2005) \( (M = 7.6) \) killed 73 thousand people.
The social consequences of devastating earthquakes:
Earthquakes come first among natural disasters in the scale of damage and the number of claimed human lives.
In recent years, the number of victims and losses during catastrophic earthquakes has not tended to decrease, and this is mainly due to a sharp increase of the population in seismically dangerous areas.
Demand analysis:
To this date, the relevance of research on the operational recovery of railways after an earthquake by monitoring transport facilities is obvious, both at national and global levels, because rail transport plays a huge role in the economies of countries, the delivery of rescuers and the evacuation of the affected population.
According to experts (Kazpravda, 2018), in the event of a devastating earthquake in Almaty, 350 thousand people can die. Thirty-five thousand structures will be destroyed, of which more than one hundred and twenty are schools and preschool institutions. Five hundred km of roadway and more than three thousand km of power systems will also be destroyed.
According to the portal Prohunt.kz (Kazpravda, 2018), Almaty is one of the three most vulnerable cities from earthquakes in the world (Figure 54.).
According to the calculations of JSC National Company Kazcosmos, only 350,000 human losses will lead to the damage of $ 28.5 billion (Казкосмос, 2006).

Investments in the project to create a monitoring system for information structures of railway transport in the Republic of Kazakhstan will be economically justified, since the project has important social and scientific significance.

**Summary – theses**

Based on the above analysis, it can be concluded that the railway can provide a decisive solution to mitigate the effects of earthquakes. To this date, the potential of railway transport has not been fully explored and it can play a major role in saving people in the event of a natural disasters.

I would like to see the following: in case of natural disasters, proceeding from the foot, the railway infrastructure is more resistant to damage comparing with other modes of transport;

- in many countries, the railway is a monopolist in the field of transportation.
- the railway has its own system;
- large carrying capacity (the length of one train is 3000 tons and a length of 1200 meters), also does not depend on weather conditions, time of year, long-distance transportation, environmental friendliness and low cost of transportation;
- Full dispatch centralization of traffic management increases throughput and provides complete control;
- the legislation of many countries provides for the maintenance of special forces for quick restoration and material and technical reserves for the railway.

Based on the research results, the following theses were formed.

1. I have identified that the role of railway systems in the (earthquake) response management should be considerably improved, because
   - it is underestimated today
   - the damage (caused by an earthquake) is usually less serious than that inflicted on other transport means (in case of having a well-prepared earthquake resistant infrastructure and a developed system of early monitoring of earthquakes)
   - it can be quickly recovered to the operational (usable) level within 6–24 hours (in case of having a conventional system) or 30 days maximum (in case of having a high-speed train system that requires preliminary test runs of trains)
it is especially relevant for countries having a limited road system and/or high risks of earthquake occurrence.

2. From extensive literature survey, including the available historical data, methods for estimating the damage, applicable models and methodologies I have found that a special response management methodology might be developed by synthetizing the available set of models and methods based on:
   - response to the railway damages caused by an earthquake,
   - collection of historical data on the railway system recovery after earthquakes including primary and secondary effects and aftershocks,
   - evaluation of the damage by introducing a new indicator – relative unusable track length (like a parameter of the lost capacity),
   - selection, improvement and development the sub-models for supporting response and recovery management.

3. I have developed an active and adaptive respond and recovery management methodology to earthquake damage of railway system that is:
   - based on recurring cycles of the zero + six + one steps,
   - including semi empirical situation awareness – evaluation – decision making between each steps,
   - supported by the discussed sub-models employing different theoretical, semi-practical calculations and simulations.

4. I have applied the developed active, adaptive response to earthquake damage to railways in the simulations and concept validation tests that:
   - applied the available historical data about railway damages caused by earthquakes and fast recovery,
   - followed experts’ recommendations advising possible decisions in different simulated situations and
   - used simulation models employing approximation of the relative unusable track length, changing process by a Markov chain, that was adapted to the applied decision at each step and includes a Monte-Carlo simulation of the possible occurrence of the aftershocks (and secondary effects),
   - were tested by invited experts having practice in disaster management and
   - demonstrated the applicability of the introduced methodology.

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105.


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