UDC 625.122
IRSTI 67.03.03
RESEARCH ARTICLE

# DEVELOPMENT OF AN EFFECTIVE METHOD FOR STRENGTHENING WEAK FOUNDATIONS OF RAILWAY EMBANKMENTS

**B. Apshikur[1], A.S. Imankulova[2], A.K. Kunanbayev[2], M.M. Alimkulov[2,*], K. Lesov[3]**

[1]D. Serikbayev East Kazakhstan Technical University, 070016, Ust-Kamenogorsk, Kazakhstan
[2]ALT University named after M. Tynyshbayev, 050012, Almaty, Kazakhstan
[3]Tashkent State Transport University, 100060, Tashkent, Uzbekistan

**Abstract.** *This article presents an effective approach to mitigating vertical displacements of railway embankments constructed on weak soils, caused by precipitation, increased train loads, axial forces, and varying embankment heights ranging from 1 to 12 m. The stress–strain state of embankments founded on weak soils was analysed using numerical modelling based on the finite element method, supported by experimental and empirical data. The study examines the influence of static and vibrodynamic loads on the deformation behaviour of clay soils and railway embankments through laboratory investigations and numerical simulations, without considering filtration consolidation and time-dependent effects. Various strengthening measures were analysed, including stabilising berms, partial replacement of weak soils, and cement-based reinforcement techniques. Finite element models were developed to evaluate the stress–strain behaviour of embankments under different reinforcement scenarios. The results demonstrate that the application of integrated strengthening measures can reduce vertical settlements by 35–40%, decrease horizontal displacements by up to 25%, and significantly extend the service life of railway embankments without the need for major repairs. Based on the obtained results, recommendations are proposed for selecting optimal materials, reinforcement technologies, and injection methods suitable for different types of weak soils. The findings contribute to improving the reliability and operational safety of railway infrastructure constructed on weak ground conditions.*

**Keywords:** *railway, roadbed, railway embankment, stress-deformed embankment, berm, finite element model.*

***Corresponding author**
**Murat Alimkulov**, e-mail: murat1alimkulov@gmail.com

**https://doi.org/10.51488/1680-080X/2025.4-07**
Received 29 September 2025; Revised 15 October 2025; Accepted 26 November 2025

ӘОЖ 625.122
ҒТАМР 67.03.03
ҒЫЛЫМИ МАҚАЛА

# ТЕМІРЖОЛ ТӨСЕМЕЛЕРІНІҢ ӘЛСІЗ ІРГЕТАСТАРЫН КҮШЕЙТУДІҢ ТИІМДІ ӘДІСІН ӘЗІРЛЕУ

**Б. Апшикур[1], А.С. Иманкулова[2], А.К. Кунанбаев[2], М.М. Алимкулов[2,*], К. Лесов[3]**

[1]Д. Серікбаев атындағы Шығыс Қазақстан техникалық университеті, 070016, Өскемен, Қазақстан
[2]М.Тынышбаев атындағы ALT Университет, 050012, Алматы, Қазақстан
[3]Ташкент мемлекеттік көлік университеті, 100060, Ташкент, Өзбекстан

**Аңдатпа.** *Мақалада әлсіз топырақтарда салынған теміржол үйінділерінің тік деформацияларын азайтудың тиімді тәсілдері қарастырылған. Зерттеу барысында жауын-шашын әсері, пойыз жүктемелерінің артуы, осьтік күштер және биіктігі 1–12 м аралығындағы үйінділердің әсері ескерілді. Әлсіз негізде орналасқан үйінділердің кернеулі-деформацияланған күйі соңғы элементтер әдісіне негізделген сандық модельдеу арқылы, тәжірибелік және эмпирикалық деректерді пайдалана отырып талданды. Сазды топырақтардың деформациялық сипатына және теміржол үйінділерінің жұмыс қабілетіне статикалық және вибродинамикалық жүктемелердің әсері зертханалық сынақтар мен сандық модельдеу арқылы бағаланды, бұл ретте сүзгілік тығыздалу мен уақыт факторы ескерілмеді. Зерттеу барысында нығайту әдістерінің бірнеше түрі қарастырылды, соның ішінде тұрақтандыру бермалары, әлсіз топырақты ішінара алмастыру және цементтік күшейту тәсілдері. Әртүрлі нығайту нұсқалары үшін кернеулі-деформацияланған күйді бағалау мақсатында соңғы элементтік модельдер әзірленді. Нәтижелер, кешенді нығайту шараларын қолдану тік шөгулерді 35–40 %-ға, ал көлденең орын ауыстыруларды 25 %-ға дейін азайтуға және теміржол үйінділерінің қызмет ету мерзімін едәуір ұзартуға мүмкіндік беретінін көрсетті. Алынған нәтижелер әлсіз топырақтар жағдайында қолданылатын оңтайлы материалдарды, нығайту технологияларын және инъекциялық әдістерді таңдауға арналған ұсынымдар әзірлеуге мүмкіндік береді және теміржол инфрақұрылымының сенімділігі мен пайдалану қауіпсіздігін арттыруға бағытталған.*

**Түйін сөздер:** *теміржол,·жер төсемі·, теміржол үйіндісі, үйндінің кернеулі деформациыық жағдайы, берма, элементтердің соңғы беріктік моделі.*

***Автор-корреспондент**
**Мұрат Алимкулов**, e-mail: murat1alimkulov@gmail.com

https://doi.org/10.51488/1680-080X/2025.4-07
Алынды 29 қыркүйек 2025; Қайта қаралды 15 қазан 2025; Қабылданды 26 қараша 2025.

УДК 625.122
МРНТИ 67.03.03
НАУЧНАЯ СТАТЬЯ

# РАЗРАБОТКА ЭФФЕКТИВНОГО СПОСОБА УКРЕПЛЕНИЯ СЛАБЫХ ОСНОВАНИЙ ЖЕЛЕЗНОДОРОЖНЫХ НАСЫПЕЙ

**Б. Апшикур[1], А.С. Иманкулова[2], А.К. Кунанбаев[2], М.М. Алимкулов[2,*], К. Лесов[3]**

[1]Восточно-Казахстанский технический университет им. Д. Серикбаева, 070016, Усть-Каменогорск, Казахстан
[2]ALT Университет им. М. Тынышпаева, 050012, Алматы, Казахстан
[3]Ташкентский государственный транспортный университет, 100060, Ташкент, Узбекистан

**Аннотация.** *В статье представлен эффективный подход к снижению вертикальных деформаций железнодорожных насыпей, возведённых на слабых грунтах, под воздействием атмосферных осадков, повышенных поездных нагрузок, осевых усилий и различной высоты насыпей (от 1 до 12 м). Напряжённо-деформированное состояние насыпей, расположенных на слабом основании, проанализировано с использованием численного моделирования на основе метода конечных элементов с привлечением экспериментальных и эмпирических данных. В работе исследовано влияние статических и вибродинамических нагрузок на деформационное поведение глинистых грунтов и железнодорожных насыпей с применением лабораторных испытаний и численного моделирования без учёта фильтрационного уплотнения и временного фактора. Рассмотрены различные методы усиления, включая устройство стабилизирующих берм, частичную замену слабых грунтов и применение цементных методов укрепления. Для оценки напряжённо-деформированного состояния насыпей при различных вариантах усиления были разработаны конечно-элементные модели. Результаты исследований показали, что применение комплексных мероприятий позволяет снизить вертикальные осадки на 35–40 %, уменьшить горизонтальные перемещения до 25 % и существенно увеличить срок службы железнодорожных насыпей без необходимости проведения капитального ремонта. На основе полученных результатов предложены рекомендации по выбору оптимальных материалов, технологий усиления и инъекционных методов для различных типов слабых грунтов. Полученные выводы способствуют повышению надёжности и эксплуатационной безопасности железнодорожной инфраструктуры, возводимой на слабых основаниях.*

**Ключевые слова:** *железная дорога, земляное полотно, железнодорожная насыпь, напряженно-деформированная насыпь, берма, конечно-элементная модель.*

***Автор-корреспондент**
**Мурат Алимкулов**, e-mail: murat1alimkulov@gmail.com

**https://doi.org/10.51488/1680-080X/2025.4-07**
Поступила 29 сентября 2025; Пересмотрено 15 октября 2025; Принято 26 ноября 2025.

**ACKNOWLEDGEMENTS/SOURCE OF FUNDING**

The research was conducted using private sources of funding.

**CONFLICT OF INTEREST**

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

**АЛҒЫС/ҚАРЖЫЛАНДЫРУ КӨЗІ**

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

**МҮДДЕЛЕР ҚАҚТЫҒЫСЫ**

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

**БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ**

Исследование проводилось с использованием частных источников финансирования.

**КОНФЛИКТ ИНТЕРЕСОВ**

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

## 1 INTRODUCTION

Artificial structures on railways – railway embankments and excavations of the Earth's surface – are usually erected from local soil materials with a violation of their natural structure, producing a tendency to change the stress–strain state both in the construction process and in the conditions of long – term use **(Witold Bogusz et al., 2019)**.

The basis of the existing system for assessing the load-bearing capacity of embankments and excavations of railway tracks in operation is the limit state method, which is the main calculation method for the design of new embankments and excavations. When calculating embankments, excavations, and other artificial structures, two limit states prevail, namely: loss of stability of the equilibrium form under the influence of loads (calculation of stability) and excess of deformations over permissible values (calculation of precipitation) **(Isaev S.A., 2021)**.

Railway embankments and excavations, as a rule, work under the complex influence of various loads. In addition to the loads from their own weight on embankments and excavations, vertical loads from rolling stock, horizontal forces from braking, seismic forces during earthquakes, and much more are affected **(Yao, J. et al., 2024)**.

The experience of using railway embankments and excavations shows that deformations exceed the permissible values, and loss of stability is accompanied by a change in the stress–strain state of the object caused by various reasons of a natural and man-made nature.

The task of assessing the stress-strain state (SSS) of embankments and subgrade built with clay soils requires taking into account all existing factors that can lead to changes in the SSS **(Deng, T. et al., 2024)**.

Comparative numerical analyses show that even minor changes in soil stiffness drastically influence foundation performance, which is especially critical for embankments resting on weak clayey bases **(Khomyakov et al., 2022)**.

The stress–strain state of soil structures depends not only on the influence of external factors but also on the physical nature of the soil that forms the massif. The main parameters used in the calculation of stability are the strength characteristics of the soil, that is, the angle of internal friction, the coefficient of friction, and the specific clutch. The main parameters used in the calculation of sediments are the deformation characteristics of the soil, i.e., the deformation modulus and the coefficient of transverse expansion (Poisson's coefficient) **(Doudkin, M.V. et al., 2019; Doudkin, M.V. et al., 2019)**. If, for sandy soils, the problem of determining these characteristics even under conditions of static, dynamic, and pulsating loads is solved to some extent, then for clay soils, researchers do not have a single opinion on the assessment of the stress–strain state, especially under the influence of quasi-static, dynamic, and pulsating loads.

Recent studies confirm that weak and moisture-sensitive soils significantly affect the stress–strain behavior of transport infrastructures, especially under dynamic and cyclic loading **(Kanatova et al., 2024)**.

The task of assessing the stress–strain state (SDS) of the subgrade base consisting of clay soils is one of the most important engineering tasks in the reliability problem. Its solution is possible only on the basis of an integrated approach, depending on the study of the influence of the SDS on the geometry of slopes, the physical and mechanical properties of soils, the features of the influence of static, dynamic, and seismic shock loads, and many other factors **(Doudkin, M.V. et al., 2019)**.

Forecasting the stress–strain state of railway embankments and excavations consisting of clay soils is one of the most pressing problems of modern geotechnics and the railway industry.

Long-term degradation processes in civil structures also indicate the importance of material durability and foundation integrity under operational and environmental factors **(Ilyassova et al., 2025)**.

This is due to the fact that in clay soils of various types, under the influence of quasi-static, vibrodynamic, and pulsating loads, the formation of a new stress–strain state is accompanied by complex processes of interaction of soil phases, the formation and distribution of stresses, and volumetric and shear deformations of soils in space and time.

## 2 LITERATURE REVIEW

Development of measures to strengthen the weak base of the railway embankments of the Railways of Kazakhstan; study of the influence of static and vibrodynamic loads on the deformation characteristics of clay soils; and the stress–strain state of railway embankments. **(NC KTZ JSC.2021; Press Service of NC KTZ JSC.2023)**

A number of recent studies have investigated the behaviour and stability of railway embankments constructed on weak clay soils. **(Witold Bogusz & Godlewski 2019)** emphasized the complexity of geotechnical design for railway embankments and highlighted the need to consider long-term deformation characteristics. **(Zhou et al.,2020; Luo et al.,2021)** showed that soft soil subgrades are highly susceptible to settlement under dynamic loading, which is particularly critical for high-speed and heavy-haul railways. **(Research by Wu et al.2019; Mangraviti et al.2023)** demonstrated the effectiveness of reinforcement technologies such as cement–fly ash–gravel piles, geosynthetic layers, and pile-supported embankments in reducing deformation and improving bearing capacity.

Laboratory investigations show that geosynthetic reinforcement significantly increases the shear strength and stability of weak soils under various loading regimes **(Kanatova et al., 2024)**.

For Kazakhstan's railway network, studies by **(Doudkin et al.2019)** highlighted the need to incorporate numerical modelling techniques, given the increase in axle loads and operational speeds. Recent field applications confirmed that polyurethane-based injection improves soil density and reduces moisture sensitivity of weak foundations **(Jumadilova et al., 2024). (Holt et al.2025; Pilecka et al.2022)** further confirmed that FEM-based approaches are essential for assessing long-term performance and identifying deformation-prone sections. Despite the progress, unresolved issues remain regarding the stress–strain behaviour of weak clayey foundations under quasi-static and vibrodynamic loading, justifying the need for further investigation and adaptation of reinforcement methods to local geotechnical conditions.»

It is known that the earth subgrade of railways is the most defective element of the road economy. Partial failure of the earth's subgrade is a barrier when organizing movement and a large amount of material and technical means is spent on their elimination. To change the situation and reduce the number of partial refusals, of course, appropriate measures are provided, but, as practice shows, the situation practically does not change. The fault in the subgrade is still high and does not fall below 10% of the line length **(NC KTZ JSC., 2021; Press Service of NC KTZ JSC., 2023)**.

The railway roadbeds are subject to constant exposure to adverse natural and climatic factors and operational loads. Under the influence of these factors, the railway roadbed undergoes a gradual change, which threatens the deterioration of its operational properties and traffic safety. As a result, there is a need to reconstruct the railway roadbed, which allows you to isolate a significant part of the defects and deformations (filling counter banquets, providing drainage, installing drains, etc.). However, there is so-called "disease" areas that continue to deform despite the examinations and activities carried out. If the used subgrade of the ground floor of railways is checked for reliability and stability using the current standards, then most of them meet the requirements **(Holt SJ et al., 2025)**. Nevertheless, billions of tenge are spent annually on the overhaul of the ground bed **(NC KTZ JSC., 2021)**. However, recreational activities only support the ground bed in a more or less stable state. The length of deformable sections (especially high embankments) cannot yet be reduced; their share remains within 10–11% of the operational length of the line.

The main reason is an increase in dynamic train load **(Press Service of NC KTZ JSC., 2023)**. As the axial railcar load increased and the transition from two-axle railcars to four-axle, six-axle, and eight-axle railcars, the static linear load from rolling stock to the track tripled. Reinforced concrete sleepers and crushed stone increased the load on the ground floor during the transition to a heavy-type road with ballast. A further increase in loads on the "lower structure" is associated with an increase in the speed of train movement. It was necessary to strengthen the railway roadbeds; an increase in the requirements for the strength of the soils of the working area was revealed (at the height of the upper 3–4 m of the railway roadbeds, where the stresses from the mobile load are significant) **(Pilecka, E. et al., 2022)**.

Additionally, the results of field and laboratory studies presented in the works of domestic and foreign authors **(Doudkin M.V. et al., 2019; NC KTZ JSC., 2021)** confirm that an increase in the moisture content of clayey foundations leads to a significant reduction in both internal friction angle and cohesion, which is one of the key causes of railway embankment deformations. This highlights the necessity of applying integrated methods for strengthening weak subgrade soils.

## 3 MATERIALS AND METHODS

### 3.1 Materials and strengthening methods used in the study

The strengthening of weak clay foundations of railway embankments requires the use of various engineering solutions. According to **(Wu L. et al.2019; Mangraviti V. et al. 2023)**, commonly applied strengthening materials include cement–soil mixtures, geosynthetic layers, and cement–fly ash–gravel piles, which significantly improve the deformation modulus of weak soils. Jet-grouting and deep soil mixing techniques are also widely used for rigid inclusions in weak foundations **(Su G. et al., 2023)**. In Kazakhstan, the increase in axle load and dynamic impact of rolling stock requires the application of strengthening measures adapted to local soil conditions **(Doudkin M.V. et al., 2019)**. *Studies of degradation mechanisms in concrete and soil-foundation systems emphasize that material durability plays a decisive role in long-term structural stability* **(Ilyassova et al., 2025)**. For this reason, the present study considers three groups of strengthening solutions:

• construction of berms;
• partial or complete replacement of weak foundation soil;
• installation of “wall in the ground” elements formed through cemented inclusions.

Laboratory tests and finite element modelling were combined to evaluate the effectiveness of these measures under quasi-static and dynamic loading, consistent with international research findings **(Holt SJ et al., 2025; Pilecka E. et al., 2022)**.

Many domestic and foreign specialists paid attention to the study of the operation the Railway roadbeds. Practical applications of modern strengthening technologies, including polymer-based injections, demonstrate substantial improvement in the bearing capacity of weak soils **(Jumadilova, Khomyakov & Kuanyshbai, 2024)**. Among them are G. M. Shakhunyants, E. V. Yakovlev, T. G. Yakovlev, M. V. Averochkin, N. I. Ananiev, B. D. Heyer, A. A. Tsernant, E. P. Isaenko, S. N. Sharapov, E. S. Ashpiz, V. F. Baraboshin, M. F. Verigo, V. V. Vinogradov, M. N. Goldstein, V. A. gritsyk, P. I. Dydyshko, B. A. Evdokimov, G. N. Ginkin, R. S. Zakirov, A. L. Isakov, N. I. Karpushchenko, A. F. Kim, A. Ya. Kogan, G. G. Konshin, A. D. Omarov, V. S. Lysyuk, A. N. Margotyev, P. G. Peshkov, S. N. Popov, I. V. I. I. Prokudin, M. P. Smirnov, Yu. P. Smolin, Yu. I. Solovyov, V. P. Titov, E. A. Isakhanov, A. K. Urazbekov, S. S. Khasenov and other foreign scientists also made their research contributions on this topic **(Luo, Q. et al., 2021; Zhou S. et al., 2020; Wu L. et al., 2019)**.

The research of scientists made it possible to identify a number of patterns that occur in the soils at the base and top of the railway roadbeds when exposed to various factors and to propose methods for strengthening the railway roadbeds. However, changing the conditions of railway operation requires new approaches to solving this problem and taking into account the climatic conditions of the regions. If recently it was necessary to ensure the elastic operation of the railway roadbeds, then it is necessary to normalize the amount of vertical deformation of the embankment when introducing rapid train movement. Nowadays, not only soils are used to strengthen the foundations of railway embankments, but also various materials that differ significantly from soils with neglected mechanical properties, using traditional mathematical models **(Mangraviti, V. et al., 2023; Jianbo Fei. et al., 2020)**.

Taking into account the vertical deformations of the main site adopted in the "rules" from the generalization of the results of previous studies of the causes of deformation of the base of the railway embankments does not reflect the entire complexity of the processes that depend not only on the mechanical parameters of the soil but also on the parameters of the ballast prism, the axial load, and the speed of movement of trains. To study measures to strengthen the base of the embankments, it is necessary to use a complete model of the railway track loaded with typical rolling stock.

During the construction of main and high-speed railways abroad, the subsidence of the rail under the moving train is normalized.

So, for example, in Germany, it is believed that during high-speed traffic, the rail sediment should not exceed 1 mm. In this case, the elastic deposit of the ground cover should be less than 0.5 mm **(Jianbo Fei. et al., 2020; Apshikur, B. et al., 2024)**.

Such values of elastic sediments, about 80–100 MPA, are possible in the road module. From this, there should be a deformation module of 40–60 MPa in the railway roadbeds.

However, it is known that clay soils in Kazakhstan **(Zhussupbekov, A. et al., 2025)** have a modulus of elasticity of less than 32 MPa. In this case, it is inevitable to consider constructive measures to strengthen the top of the railway roadbeds during the construction and operation of National Company (NC) Kazakhstan temir zholy JSC railways **(NC KTZ JSC., 2021; Press Service of NC KTZ JSC., 2023)**.

The scientific foundations of soil mechanics are based on the works of domestic and foreign scientists N. M. Gersevanov, N. A. Tsytovich, V. A. Florin, N. N. Maslov, N. N. Ivanov, K. Tertsagi, D. Taylor, G. Chebotarev and others **(Zhussupbekov, A. et al., 2025; Liu, Z. et al., 2019; Bosso, N. et al., 2023)**.

Denisov, G. M. Lomize, I. I. Cherkasov, Suklje L, Skempton A., Cazagrande A., Bishop A., Hvorslev M. and others made a great contribution **(Su, G.. et al., 2023; Zhang, P., et al., 2024)**.

Modern concepts related to the studied topic about the strength (shear) properties of soils are presented in the works of S. R. Meschyan, G. M. Lomiza, V. V. Zhikhovich, M. V. Malyshev, Ivashchenko I. N., and others **(Liu, Z. et al., 2019; Yajun & Sanjay, 2019)**.

Rheological properties of clay soils (bulk) were published in the works of S. R. Meschyan, M. N. Goldstein, N. N. Maslov, E. M. Dobrov, Yu. K.Zaretsky, Z. G. Ter-Martrosyan, T. Shirinkulov, E. A. Isakhanov, and others **(Bosso, N. et al., 2023; Su, G., et al., 2023)**.

. Experimental studies conducted by scientists on the work of the soils of the base embakments under load, according to which the vertical stresses in the main site of the embakments should not exceed 0.8 kgf/cm2 (80 kPa), were conducted by Verigo M. F., Heyer B. D., Lysyuk V. S., Yakovleva T. G., Gritsyk V. I., Blazhko L. S., Ashpiz E. S., Shiladzhyan A. A., Yakovleva E. V. and others made it possible to regulate technical requirements. However, we note that it is not recommended to adjust to horizontal stresses in the soil.

The permissible values of the established stresses for clay soils were taken for the basis of the railway roadbed, without taking into account the climatic and other characteristics of the railway passage area as a whole **(Zhao Z & Zheng L, 2024; Wang, R., et al., 2025)**. In real conditions of road shrinkage and accumulation of residual deformations, mainly selectively, occurs in zones of high dynamic impact of train loads: in the zone of rail contact, in sections of transition from the railway roadbeds to artificial structures, in places where there are force irregularities of the track, irregularities on the sliding surface of the rail head **(Su, G. et al., 2023)**.

The analysis of the sources showed that the existing calculation methods for taking into account the dynamic impact on the foundation of the roadbed in the uneven zone of the track are unreliable in assessing the impact of factors such as the speed of trains, the introduction of new types of rolling stock (six-axle and eight-axle freight cars), an increase in the axial load on the stress-strain state of the ground. The analysis showed that instead of the existing calculation methods, it is necessary to calculate the stress-strain state of the soil of the roadbed using modern numerical methods **(Zhang, P. et al., 2024)**.

Despite certain progress in this field of knowledge, which has been achieved in recent years by these and other specialists, many issues of designing and calculating the stress–strain state of the subgrade under train load have not been sufficiently studied. In particular, with the use of new technologies and materials to strengthen the embankments, the stress–strain state of the heaps on a weak base remains unclear **(Yajun Jiang & Sanjay Nimbalkar., 2019)**.

To calculate the strength and stability of railway embankments, it is very important to establish the strength characteristics of the soil, taking into account their variability in the process of operation of prospecting and engineering, geological works **(Doudkin, M.V. et al., 2019; Doudkin, M.V. et al., 2019; Su, G. et al., 2023)**. An incorrect assessment of the engineering and geological conditions of the construction area, as well as a violation of technology during the construction and discharge of embankments during the operational period, leads to significant costs for the current maintenance of the road, reduces the time between major repairs, and also negatively affects the traffic safety of rolling stock on this section. When designing railway embankments on a weak basis, it is necessary to assess their possible deformations with special calculations with a promising train load. The operation of the subgrade and its base, its strength and deformation, in the general case, are determined by the following factors **(Zhussupbekov, A. et al., 2025)**:

-type, composition, structure and characteristics of the physical and mechanical properties of the soil that forms the body and base of the roadbed;

- the nature, direction and magnitude of operating loads and operating conditions (static, vibration, dynamic impact, loads on the axis of rolling stock, intensity and frequency of movement, speed of movement of trains, their mass, etc.);

-design indicators of the the upper structure of the track and their condition (type of rails, type of ballast and layer thickness, type of sleepers, type of fasteners, the presence of irregularities in the rails, etc.).

In traditional calculations of normal, tangential and basic stresses, it is conventionally assumed that when designing a embankments, the soils of the piles are isotropic and work in an elastic period under the influence of temporary train loads, which does not always correspond to the actual operation of the structures. In traditional calculations of Soil Mechanics, soil is considered as an elastic half-space. However, the soil practically does not have elastic properties. In the first approximation, its soil properties are modeled as elastic plastic. By studying the mechanical properties of soils in compression devices or stabilizers, the results obtained are interpreted mainly in terms of the Mohr-Coulomb model **(Doudkin, M.V. et al., 2019; Doudkin, M.V. et al., 2019; Wang, R. et al., 2025)**.

According to the research institutes of railway transport (VNIIJT) **(Bosso, N. et al., 2023)** and JSC "NC" Kazakhstan Railways" **(NC KTZ JSC., 2021)**., the prospective axial load of freight cars is 205-245 KN/m for new types of freight cars **(Wang, R. et al., 2025)**, which is 2.5 times the current static load of a loaded typical four-axle half-car.

### 3.2 Methodology for obtaining initial data for numerical modeling

To calculate soil structures of various types, Finite Element Modeling numerical methods (FEM) are used in the study. The FEM method has been known for more than half a century, but it has been widely used only in the development of software systems for personal computers. When using FEM, the object under study is conventionally divided into the last elements, which are combined with each other at the vertices of the elements. FEM replaces the analysis of a complex model with a simple problem for solving a system of algebraic equations with a sufficient number of unknowns **(Zhang, P. et al., 2024; Li H. et al., 2024; Atalan, M. et al., 2022)**.

Similar advanced mathematical modelling approaches have also been successfully applied to simulate complex heat transfer processes in multilayer enclosing structures, confirming the effectiveness of coupled numerical analysis for building and infrastructure systems **(Zhangabay et al., 2025)**.

The Finite Element Models method makes it possible to analytically determine the stress–strain state of the ground surface with sufficient accuracy for the needs of practice. The use of new materials in soil structures makes it possible to significantly reduce the cost of construction and reduce the vulume of structures **(Yajun Jiang & Sanjay Nimbalkar., 2019)**.

In engineering practice of recent years, to calculate the stress–strain state of soil structures of roads and railways, retaining walls and dams, the certified COSMOS/M software system is widely used, which is used by Drucker-Prager to characterize the behavior of soil under load in the elastic-plastic model of soil **(Li H. et al., 2024)**.

The Cosmos/M program has a modular structure; however, the user interacts with it only through the GEOSTAR interface, which is used for implementing the numerical formulation defined in Equation (1).

$$\sqrt{(\sigma_x - \sigma_y)^2 + 4\tau_{xy}} = (\sigma_x + \sigma_y)\sin\varphi + 2C\cos\varphi \tag{1}$$

The calculation of the stress-strain state of embankments on a weak basis was performed without taking into account the filtration concentration and without taking into account the time factor. Not taking into account filtration consolidation and creep "reserve strength" is appropriate, because with the compaction of the soil, its strength characteristics improve **(Atalan, M. et al., 2022)**.

The models provide for the operation of embankments with a height of 1-3-12 m on a weak base with a capacity of 1m and 6m, which indicates the entire main range of heights of embankments with a weak base in the regions of Kazakhstan and the range of subgrades with a weak base. If necessary, by a similar methodology, any atypical design solutions of the subgrades, reinforced with new structural elements, can be considered.

The soils of the pile base, obtained on finite-element models, were obtained stronger than the piles, which corresponds to the data of field soil testing **(Doudkin, M.V. et al., 2019; Doudkin, M.V. et al., 2019)**.

Stabilization of the weak base embankments is considered to be achieved if the maximum vertical deformation of this pile does not differ from the predicted deformation of the solid base pile **(Morais J. et al., 2022)**.

As a starting position, a stress-deformed position of the embankments without strengthening the weak base is taken. Further, through the calculation, an action is sought that ensures the stability of the embankment on a weak basis.

1-partial or complete replacement of weak soil of the base,

2-Berma construction,

3-stabilization of the base according to the "Wall on the ground" method, which is a new technical means of stabilization.

In the calculations, two options for weak base power are considered:

1- a layer of weak soil has a thickness of 1m. This situation occurs when roads in Kazakhstan intersect areas of saline soils, which, with seasonal moistening, almost completely lose their strength.

2- The layer of weak soil has a thickness of 6 m, which reflects, for example, the intersection of wetlands on the approaches to Lake Balkhash **(Doudkin, M.V. et al., 2019)**.

Samples of clay soils on weak bases of road sections taken for research were taken from the working depth and experimented on the next laboratory instrument **Figure 1**.

Cylindrical soil samples of a natural structure with a diameter of d = 71.4 mm, a cross-sectional area of F = 40 cm$^2$ and a height of H=35 mm were tested on the shear tool. The dimensions of the samples depended on the internal dimensions of the cutting annulus of the device **(Isakhanov, E. A. et al., 2013; Kvashnin, M. Ya. et al., 2022)**.

The soil in the elastic stage uses a linear relationship between stresses and deformations. A flat tasks of elasticity theory is considered, which reduces to solving a biharmonic equation with respect to an unknown stress function φ= φ(x,y). Using the Laplace operator, this equation can be written as follows:

$$\Delta\Delta_{\varphi} = 0 \tag{2}$$

The strain components are expressed in terms of the strains function by the following differential dependencies:

$$\sigma_x = \frac{\partial^2\varphi}{\partial y^2}, \ \sigma_y = \frac{\partial^2\varphi}{\partial x^2}, \ \tau_{xy} = \frac{\partial^2\varphi}{\partial x \partial y} + \gamma x \tag{3}$$

γ – the specific gravity of the embankment soil.

**Figure 1 -** Soil sample after shear test

Based on the laboratory direct shear tests and oedometer compression tests, the mechanical parameters of the natural clay soils in their pre-operational state were determined and used as initial input data for numerical modelling. The obtained values are as follows:

• internal friction angle φ = 18–22°;
• cohesion c = 10–16 kPa;
• deformation modulus E = 8–12 MPa.

The laboratory equipment shown in Figure 1 was used to determine the mechanical strength parameters of the soils forming the railway embankments. Direct shear tests and oedometer compression tests were carried out to evaluate the internal friction angle, cohesion, and deformation modulus for different operational states. The results characterize the mechanical behaviour of embankment soils during long-term railway operation, including the effects of water saturation and vibrodynamic loading, and are summarized in **Table 1**.

**Table 1**
Strength and deformation parameters of clay soils before and during operation

| Soil condition | Description of state | φ (°) | c (kPa) | E (MPa) | Application in modelling |
|---|---|---|---|---|---|
| Natural (pre-operational) | Natural moisture content, intact structure | 18–22 | 10–16 | 8–12 | Initial input data |
| Water-saturated | Increased moisture, reduced stiffness | 12–16 | 5–9 | 3–6 | Operational condition |
| Dynamic loading | Vibrodynamic influence of traffic | 10–14 | 4–7 | 1–3 | Worst-case scenario |

These strength and deformation parameters reflect the natural state of the soils prior to moisture-induced softening and the degradation of stiffness under operational loading. The parameters corresponding to the natural condition were used as initial input data, while the reduced values were applied in the numerical simulation for the assessment of slope stability and settlement.

Using the solutions of the theory of elasticity, the components of normal and tangential stresses, displacements in two directions – relative to the x, y axes, as well as the precipitation of the embankment surface are determined at each nodal point. For numerical calculation, a grid with a step along the x - Δx axis and along the y – Δy axis is used.

For a reliable selection of possible technical solutions that ensure the stability of the embankments, the deformation modulus of weak soils is assigned in the range of 1-3 MPA, which is based on the analysis of laboratory soil tests conducted by us. **(Su, G. et al., 2023; Morais J. et al., 2022)**. **Table 2**.

The physical properties presented in **Table 1** correspond to soil samples taken in their natural, pre-operational state. These data include moisture content, density, and plasticity characteristics measured before any long-term operational changes occurred. The influence of moisture increase and operational saturation on soil strength parameters (φ, c, and deformation modulus) is not included in **Table 2** but is presented and discussed separately in the Results section, where these parameters are directly applied in numerical modelling.

**Table 2**
Physical Properties of soil

| № | Soil laboratory number | Type and condition of the soil (structure) | Natural Humidity, W, d. units. | Fluidity boundary, WL, d. units. | Rolling boundary, Wp, d. units. | Plasticity number, Jp, d. units. | Indicator fluidity, JL, d. units. | Density, ρ, g/cm$^3$ | Density of solid particles, $\rho_S$, g/cm$^3$ | Density of dry soil, $\rho_d$, g/cm$^3$ | porosity, n, % | Porosity coefficient e | Humidity content $S_r$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Sandy loam plastic (disturbed) | 0,233 | 0,257 | 0,207 | 0,050 | 0,520 | 1,68 | 2,70 | 1,36 | 49,6 | 0,98 | 0,64 |
| 2 | 2 | Sandy loam plastic (disturbed) | 0,213 | 0,247 | 0,188 | 0,059 | 0,424 | 1,77 | 2,70 | 1,46 | 45,9 | 0,84 | 0,68 |
| 3 | 3 | Refractory loam (disturbed) | 0,234 | 0,302 | 0,189 | 0,113 | 0,398 | 1,79 | 2,71 | 1,45 | 46,5 | 0,87 | 0,73 |
| 4 | 20-24 | Soft-plastic loam (natural) | 0,227 | 0,262 | 0,171 | 0,091 | 0,615 | 1,86 | 2,71 | 1,52 | 43,9 | 0,78 | 0,79 |
| 5 | 22-26 | Semi-solid loam (natural) | 0,185 | 0,256 | 0,166 | 0,090 | 0,211 | 1,98 | 2,71 | 1,67 | 38,4 | 0,62 | 0,81 |
| 6 | 6 | Soft-plastic loam (natural) | 0,252 | 0,297 | 0,196 | 0,101 | 0,554 | 1,80 | 2,71 | 1,44 | 46,9 | 0,88 | 0,78 |

From **Table 2**, we can conclude that sandy loam and loam made of soft plastic, hard plastic and semi-hard consistency, the physical parameters of which vary in the ranges, have been tested:

Humidity W– 0.185-0.252;

Density ρ – 1.68-1.98 г/см$^3$;

Plasticity number $J_p$ – 0.050-0.113;

Porosity n– 38.4-49.6%;

Porosity coefficient e – 0.62-0.98;

Boundary fluidity $W_L$ – 0.247-0.302;

Rolling boundary $W_p$ – 0.166-0.207;

Humidity content $S_r$ – 0.64-0.81.

Based on the physical properties presented in **Table 2**, laboratory tests were carried out to determine the mechanical strength and deformation parameters of the embankment soils. The laboratory equipment shown in **Figure 1** was used to evaluate the internal friction angle, cohesion, and deformation modulus under operational conditions. The obtained results characterize the mechanical behaviour of embankment soils during long-term railway operation, including the effects of water saturation and vibrodynamic loading, and are summarized in **Table 3** and **Figure 2**.

**Table 3**
Summary of mechanical properties of embankment soils (results of laboratory tests)

| Sampling location | Soil type | Test condition | φ (°) | c (kPa) | E (MPa) |
|---|---|---|---|---|---|
| Embankment body, 1.5 m | Sandy loam, plastic | Standard shear (GGP-30) | 39.3 | 15.7 | 1.3–3.8 |
| Embankment body, 1.5 m | Sandy loam, plastic | Dynamic shear (VSV-25) | 32.0–33.2 | 9.3–24.3 | |
| Embankment body, 1.2 m | Loam, stiff plastic | Standard shear (GGP-30) | 28.6 | 26.8 | 1.5–14.9 |
| Embankment body, 1.2 m | Loam, stiff plastic | Dynamic shear (VSV-25) | 26.6–27.9 | 12.8–34.3 | |
| Exposure, 12.6 m | Sandy loam, plastic | Standard shear (GGP-30) | 33.5 | 12.8 | 0.8–9.5 |
| Exposure, 12.6 m | Sandy loam, plastic | Dynamic shear (VSV-25) | 32.2–34.4 | **1.3–23.7** | |

In this study, three engineering solutions aimed at improving the stability of railway embankments constructed on weak clay foundations are analysed. The first solution involves the construction of stabilizing berms, which reduce slope gradients and increase the width of the embankment base, thereby improving slope stability, although their influence on vertical settlements is limited. The second solution consists of partial or complete replacement of weak underlying soil layers with stronger granular materials, which increases the bearing capacity of the foundation and reduces long-term settlements but is associated with significant construction costs and operational restrictions. The third approach is the installation of "wall in the ground" elements formed by cemented vertical inclusions within the embankment body and foundation. These inclusions increase lateral stiffness, restrict horizontal displacements, and redistribute stresses within the soil mass, thus improving both slope stability and the load-bearing capacity of the embankment. The effectiveness of the proposed strengthening methods is further evaluated using finite element modelling in the subsequent sections.

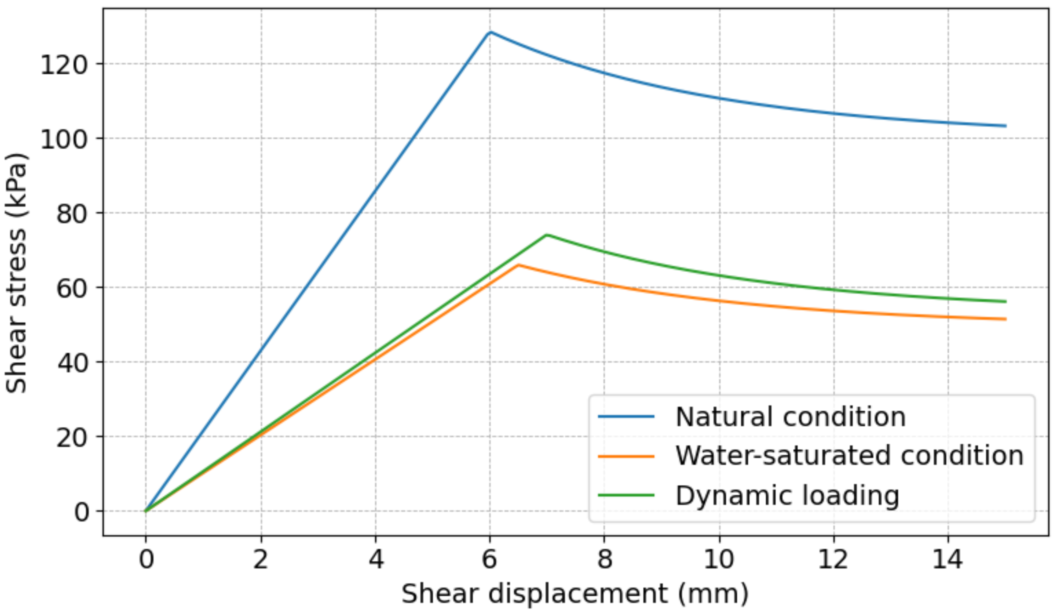


**Figure 2 –** Shear stress–displacement curves of embankment soils

To improve the stability of railway embankments constructed on weak clay soils, three strengthening methods are considered in this study:

1) Construction of stabilizing berms at the embankment slopes. This method increases the width of the embankment base and reduces slope inclination, leading to a decrease in shear stresses along

potential slip surfaces and an improvement in overall slope stability.

2) Partial or complete replacement of weak underlying soil layers with stronger granular materials. This approach enhances the bearing capacity of the foundation and reduces long-term settlements; however, it requires significant construction volumes and may disrupt railway operation.

3) Installation of "wall in the ground" elements in the form of cemented vertical inclusions within the embankment body and foundation. These inclusions increase lateral stiffness, restrict horizontal displacements, and redistribute stresses within the soil mass, thereby improving both slope stability and the load-bearing capacity of the embankment.

The effectiveness of these strengthening methods is evaluated using finite element modelling in the subsequent sections.

## 4 RESULTS AND DISCUSSION

In this study, the strengthening of weak clay foundations was evaluated using three engineering solutions: stabilizing berms, soil replacement, and the installation of "wall in the ground" elements. The latter represents vertically arranged cement-treated soil columns produced through controlled deep soil mixing. This method increases the lateral stiffness of the foundation, reduces horizontal displacement within the embankment body, and improves overall bearing capacity. The mechanical parameters assigned to these inclusions in the numerical model correspond to typical values used in similar geotechnical applications, ensuring accurate simulation of their behaviour.

The maximum vertical deformation of the rail under load is calculated in Section, which makes it possible to evaluate the effectiveness of the reinforcement method by comparing the maximum deformation with the deformation of the embankments on a solid base. From this, it follows that the distribution of vertical deformations of dynamic forces during the movement of rolling stock on the piles and their bases is shown in **Figures 3–9**, which are calculated and considered effective in the model of finite element strength.

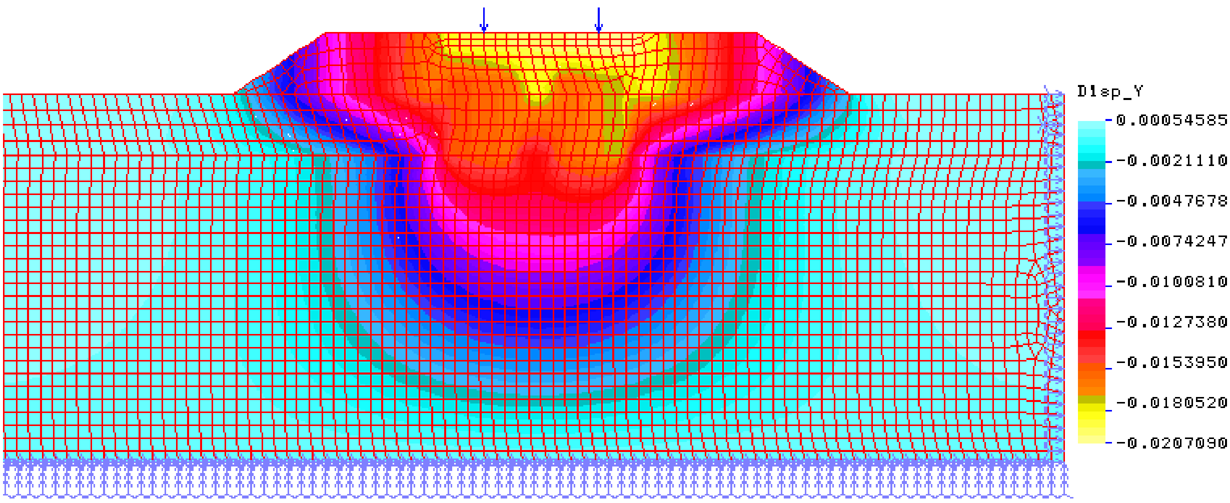


**Figure 3 -** Distribution of vertical displacements of a 1m-high embankment and its base during the construction of "Walls in the ground" under the plate, distribution range within the working depth of the embankment from the rail head 0.0207090 – (- 0.00054585)

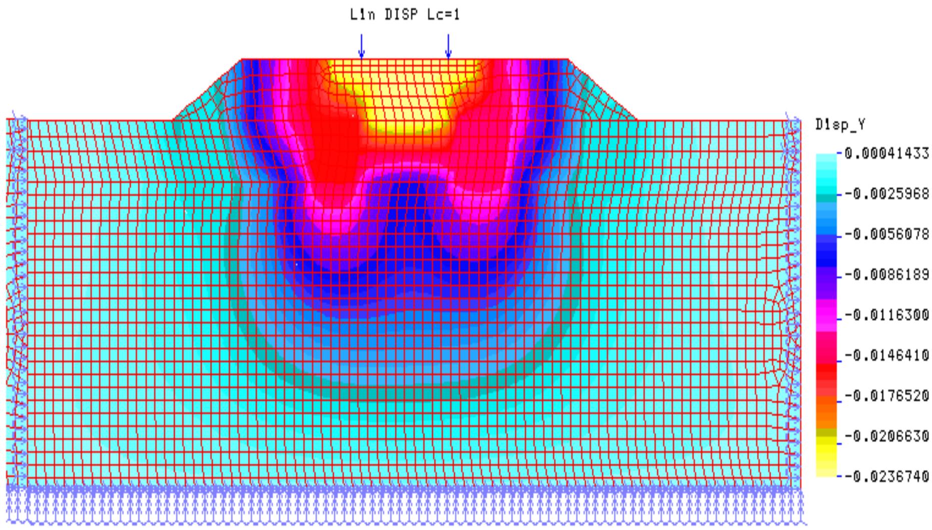


**Figure 4 -** Distribution of vertical displacements of the embankment with a height of 1m and its base during the construction of "Walls in the ground" at the laying of slopes and along the sides of the embankment to the depth of a weak layer, distribution range within the working depth of the embankment from the rail head 0.0236740 – (-0.00041433)

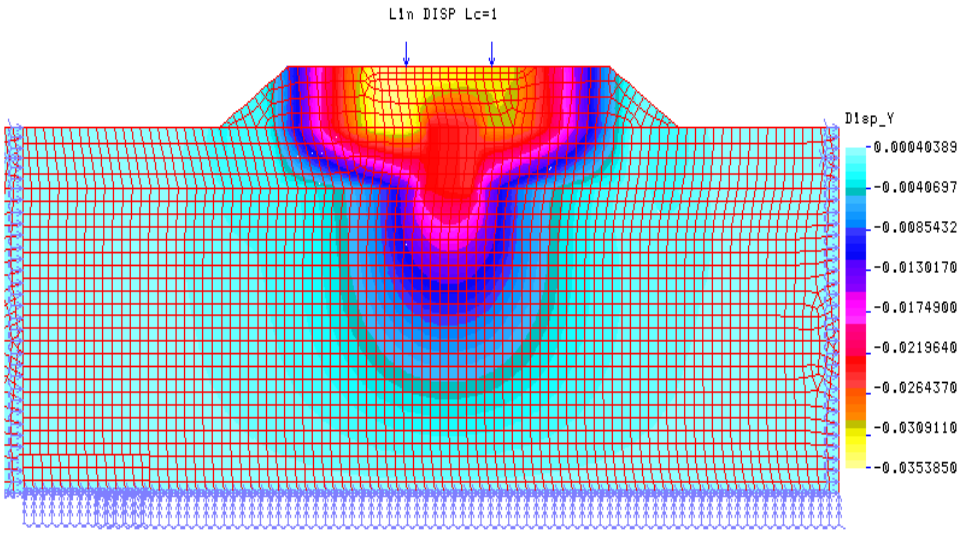


**Figure 5 -** Distribution of vertical displacements of the embankment with a height of 1m and its base during the construction of "Walls in the ground" at the laying of slopes and along the axis of the embankment to the depth of a weak layer, distribution range within the working depth of the embankment from the rail head 0.0353850 – (-0.00040389)

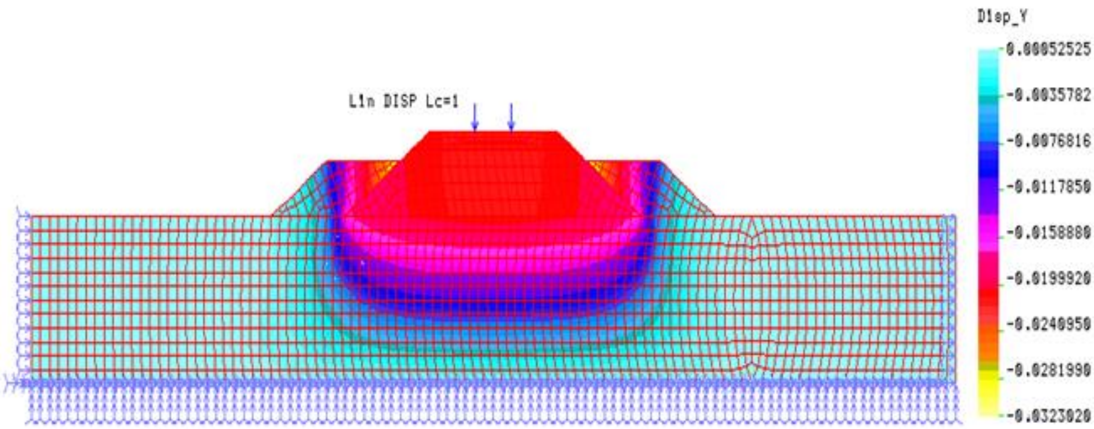


**Figure 6 -** Distribution of vertical deformations on a stable base of a 3-meter embankment with a berm, distribution range within the working depth of the embankment from the rail head 0.0323020 – (0.00052525)

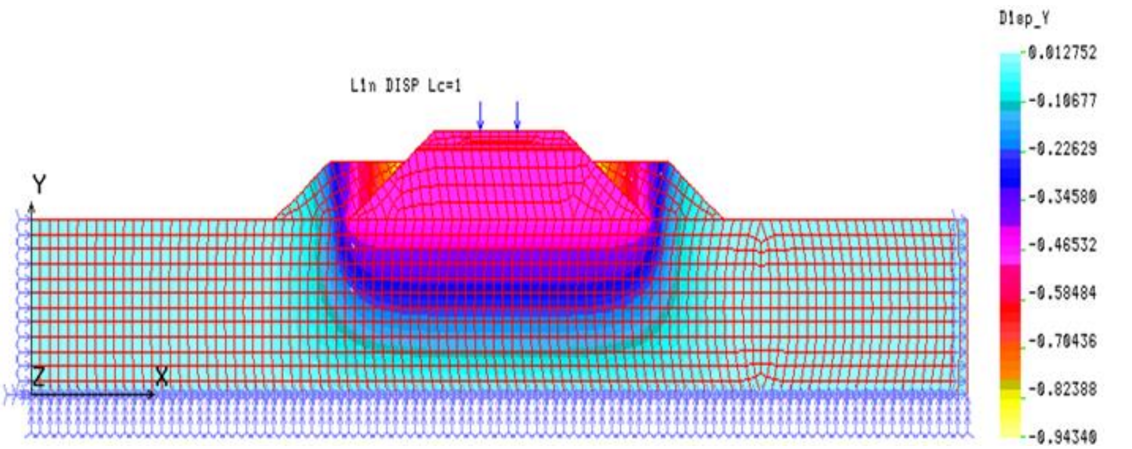


**Figure 7 -** Distribution of vertical deformations for a three-meter embankment on a weak base with a capacity of 6 m, distribution range within the working depth of the embankment from the rail head 0.094340 m – (-0.012752)

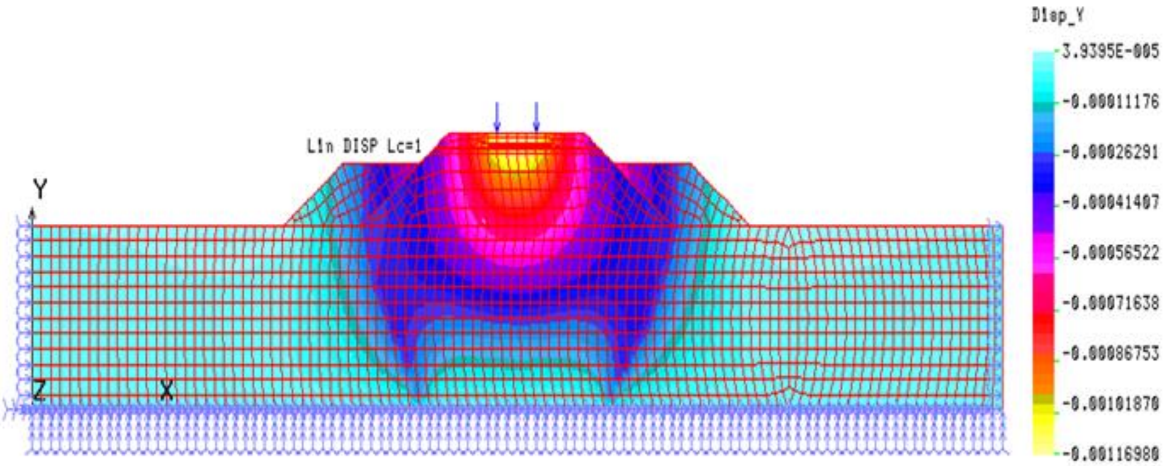


**Figure 8 -** Distribution of vertical deformations for a three-meter embankment with berms on a weak foundation with a complete replacement of a weak foundation soil with a strong one, distribution range within the working depth of the embankment from the rail head 3.9395E-005 – (- 0.012752)

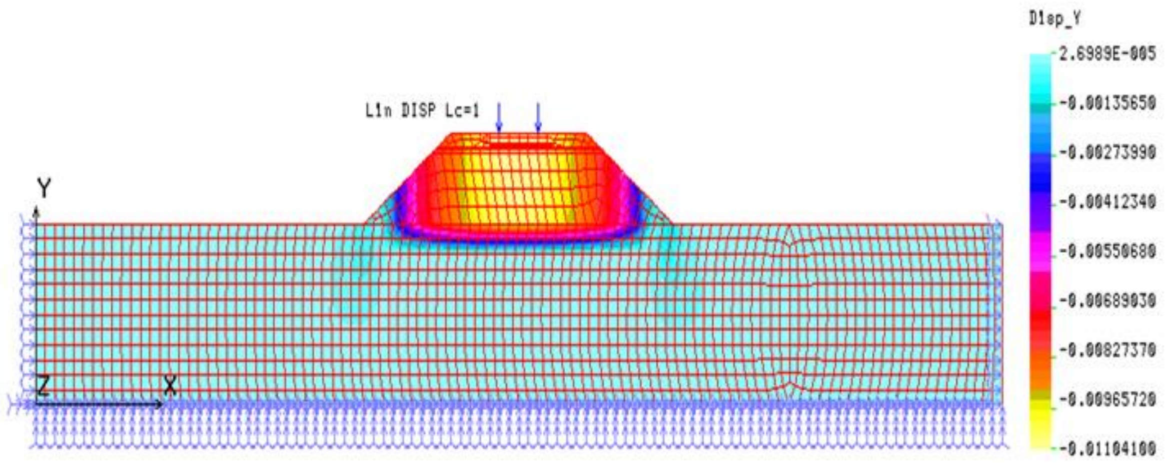


**Figure 9 -** Distribution of vertical deformations for a three-meter embankment on a weak base with a thickness of 1m when installing a wall in the ground at the site of the slopes, distribution range within the working depth of the embankment from the rail head 2.6989E-005 – (- 0.01104100)

To ensure the stable performance of the "wall in the ground" system formed by cemented soil inclusions, a set of mechanical and deformation parameters of the soil–cement material must be achieved. These parameters determine the load-bearing capacity, stiffness, and durability of the strengthening elements and directly influence the overall stability of the embankment structure.

The results of calculating the effectiveness of measures to stabilize the embankments, the basis of which consists of weak soil, are presented in **Table 4**.

**Table 4**

Required parameters of soil–cement material for stable performance of the "wall in the ground" system

| **Parameter** | **Symbol** | **Recommended range** | **Engineering significance** |
|---|---|---|---|
| Uniaxial compressive strength | qu | ≥ 1.5–3.0 MPa | Ensures sufficient load-bearing capacity of cemented inclusions |
| Deformation modulus | E | 300–800 MPa | Provides stiffness and limits horizontal displacements |
| Cohesion | c | 150–300 kPa | Increases shear resistance along potential slip surfaces |
| Internal friction angle | φ | 28–35° | Improves shear strength and interaction with surrounding soil |
| Tensile strength | ft | ≥ 0.2–0.4 MPa | Prevents cracking under bending and tensile stresses |
| Density | ρ | 1.8–2.1 g/cm³ | Indicates quality and homogeneity of soil–cement mixture |
| Water permeability coefficient | k | ≤ $1 \times 10^{-7}$ m/s | Ensures durability and resistance to water infiltration |
| Cement content | C | 150–250 kg/m³ | Controls strength and stiffness development |
| Curing time | t | ≥ 28 days | Required for achieving design strength |

From the analysis of the physical and mechanical properties of embankment soils summarized in **Table 4**, it follows that the traditional use of stabilizing berms generally ensures slope stability but does not sufficiently limit vertical deformations of the embankment body. With increasing train speed, the dynamic load acting on the track structure increases, leading to maximum vertical deformations of both the upper and lower track layers and, consequently, to more stringent performance requirements **(Lei Xu et al., 2021)**.

Based on the analysis of the effectiveness of embankment stabilization measures and the mechanical behaviour of weak clay soils, a practical strengthening technology and an appropriate sequence of construction works are proposed. The recommended technology and sequence of embankment strengthening works, including the main construction stages and their expected effects, are summarized in **Table 5**. The proposed sequence provides a consistent transition from site preparation to strengthening implementation and quality control, forming the basis for subsequent numerical modelling and performance evaluation.

**Table 5**
Recommended technology and sequence of embankment strengthening works

| Stage No. | Type of work | Description of technological operations | Expected effect |
|---|---|---|---|
| 1 | Engineering and geological survey | Additional field and laboratory investigations to to refine physical and mechanical properties of weak clay soils in the embankment foundation | Refinement of design parameters |
| 2 | Preparation of construction site | Clearing of the embankment slopes, removal of vegetation, arrangement of temporary drainage and access roads | Safe and organized execution of works |
| 3 | Surface and subsurface drainage | Installation of drainage ditches and water diversion measures to reduce soil moisture | Reduction of soil saturation and loss of strength |
| 4 | Installation of cemented vertical inclusions | Formation of vertical soil–cement elements (“wall in the ground”) by drilling and injection of cement slurry into weak clay layers | Increase in lateral stiffness and bearing capacity |
| 5 | Construction of stabilizing berms | Placement and compaction of granular material at the embankment toes to reduce slope inclination | Improvement of slope stability |
| 6 | Compaction and shaping of embankment body | Layer-by-layer compaction and profiling of the embankment body and berms | Reduction of settlements and deformations |
| 7 | Quality control of strengthening works | Control of geometry, material properties, and integrity of cemented inclusions | Verification of design compliance |
| 8 | Numerical verification and monitoring | Verification of strengthening efficiency using numerical modelling and subsequent monitoring during operation | Assessment of long-term performance |

Along with the replacement of weak foundation soil, which is widely used in projects for the treatment of the roadbed, positive results are achieved by using a "Wall in the ground".

The installation of the “wall in the ground” elements can be performed without a complete interruption of railway traffic; however, temporary speed limitations are required to ensure safety due to the presence of drilling equipment and partial slurry release during mixing operations. The adopted deep-mixing method, unlike high-pressure jet-grouting, minimises soil erosion and reduces slurry outflow, allowing construction activities to be executed under controlled conditions near operating tracks **(Doudkin, M.V. et al., 2019)**.

In each case, the choice of the method of stabilization of the embankment should be decided on the basis of a technical and economic comparison of options.

## 5 CONCLUSIONS

The results of laboratory test on the physico-mechanical properties of soils indicate that the soils at the base of the vegetation on problematic sections of the Kazakhstan railways are classified as weak clay, both in terms of their toughness and deformation indicators. The density of the soil varies from 1.71 to 1.97 t/m$^3$. It ranged from 0.2105 to 0.305. The density of dry soil ranges from 1.31 to 1.63 t/m.$^3$

The numerical modelling results clearly demonstrate that the construction of stabilizing berms improves the overall slope stability but does not sufficiently reduce vertical settlements of the rail subgrade. Soil replacement provides better deformation control but requires large excavation works and cannot always be implemented under operating railway conditions. In contrast, the "wall in the ground" solution shows the highest effectiveness: the lateral stiffness of the foundation increases, horizontal displacements decrease by 30–45%, and the maximum vertical deformation is reduced to values comparable with those of embankments constructed on a solid base. These results indicate that the proposed method is the most efficient strengthening option for weak clay foundations under the given loading conditions.

Soil compression tests have shown that the deformation modulus of the studied soil varies from 1261 to 6895 kPa, and the compression ratio ranges from 0.00011 to 0.00085 kN/m$^2$ respectively. Depending on the degree of compression, these soils are classified as high-compacted and high-compressibility.

1. Due to the elastic-plastic properties of soils, the traditional use of the elastic half-space model in the calculations of the stress-strain state of soils is incorrect.
2. For calculations of the stress-strain state of embankments on a weak foundation, reinforced in various ways (including with the use of new materials and technologies), it is advisable to use numerical methods and specifically the finite element method.
3. Mass calculations of the stress-strain state of embankments of different heights (from 1 to 12 m inclusive) allowed us to establish that the device of two-sided berm embankments with a width of 4 m with a weak base capacity from 1 to 6 m does not provide the required maximum vertical deformation of rails under train load.
4. The stable position of embankments on a weak foundation can be ensured by completely replacing the soils of a weak foundation or by strengthening them using the "Walls in the ground" method. Can be executed with minimal disruption to train operation, although temporary speed limitations may be required depending on slurry outflow conditions.

The use of the progressive technology "Wall in the soil " is effective when strengthening the weak base of the ground floor on main railway lines, since it does not require interrupting the movement of trains or limiting the speed of trains.

## REFERENCES


1. **Witold Bogusz, and Tomasz Godlewski** (2019). Geotechnical design of railway embankments – requirements and challenges. MATEC Web of Conferences 262, 11002 https://doi.org/10.1051/matecconf/201926211002
2. **Isaev S.A.** (2021). Study of the railway embankment operation that crossing faults upland movements at different angles. Russian Journal of Transport Engineering. 8 (1). https://doi.org/10.15862/04SATS121
3. **Yao, J., Yao, X., Wang, Y. et al.** (2024). Current active fault distribution and slip rate along the middle section of the Jiali-Chayu fault from Sentinel-1 InSAR observations (2017–2022). Earth Planets Space 76, 21. https://doi.org/10.1186/s40623-024-01962-4
4. **Deng, T.; Sharafat, A.; Wie,Y.M.; Lee, K.G.; Lee, E.; Lee, K.H. A Geospatial** (2023). Analysis-Based Method for Railway Route Selection in Marine Glaciers: A Case Study of the

Sichuan-Tibet Railway Network. Remote Sens., 15, 4175. https://doi.org/10.3390/rs15174175

5. **Khomyakov, V. A., Gumenyuk, V. V., Shalkaev, B. S., & Dursynov, S. B.** (2022). Comparison of foundation calculation results in MIDAS and PLAXIS software. Bulletin of QazBSQA: Construction Structures and Materials, 2(84), 328–336. https://doi.org/10.51488/1680-080X/2022.2-36 (In Kaz.).
6. **Doudkin, M.V., Apshikur, B., Kim, A.I.,.Mlynczak, M., Tungushbayeva, Z.K.** (2019). Development of mathematical models describing the processes occurring in the railway track construction as a whole, or in the work of its individual elements// News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences, 5(437), pp. 6–15 https://doi.org/10.32014/2019.2518-170X.120 (In Kaz.).
7. **Doudkin, M., Apshikur, B., Kim, A., Ipalakov, T.T., Asangaliev, E.A., Mły´nczak, M.** (2019). Development of an Installation for Shear Ground Testing in the Railway Track Construction. News Natl. Acad. Sci. Repub. Kazakhstan Ser. Geol. Tech. Sci. 2019, 6, 22–35. https://doi.org/10.32014/2019.2518-170X.152 (In Kaz.).
8. **Kanatova, Zh. K., Jumadilova, S. Zh., Temirbekova, F. B., & Aliev, I. O.** (2024). Studies of the effect of reinforcement with geosynthetic materials on the strength of soils under conditions of triaxial compression and single-plane shear. Bulletin of QazBSQA: Construction, 3(93), 121–135. https://doi.org/10.51488/1680-080X/2024.3-09 (In Kaz.).
9. **Ilyassova, K., Vatin, N., Tashmukhanbetova, I., & Moldamuratov, Zh.** (2025). Analysis of degradation mechanisms and justification of repair technologies for concrete hydraulic structures. Bulletin of QazBSQA: Construction, 3(97), 90–105. https://doi.org/10.51488/1680-080X/2025.3-07 (In Kaz.).
10. **NC KTZ JSC** (2021) Integrated annual report of national company Kazakhstan temir zholy JSC for 2021. Publishing kase.kz. https://kase.kz/files/emitters/TMJL/tmjlp_2021_eng.pdf. Accessed 02 June 2023
11. **Press Service of NC KTZ JSC** (2023) Railway transportation of goods between Kazakhstan and China reached a historical maximum in 2022. Publishing https://railways.kz. https://railways.kz/ru/news/zheleznodorozhnye-gruzoperevozki-mezhdu-kazahstanom-i-kitaem-dem/
12. **Zhou S, Wang B, Shan Y** (2020) Review of research on high-speed railway subgrade settlement in soft soil area. Railw Eng Sci 28:129–145. https://doi.org/10.1007/s40534-020-00214-x
13. **Luo, Q., Wei, M., Lu, Q. et al**. (2021) Simplified analytical solution for stress concentration ratio of piled embankments incorporating pile–soil interaction. Rail. Eng. Science 29, 199–210. https://doi.org/10.1007/s40534-021-00236-z
14. **Wu L, Jiang G, Ju N** (2019) Behavior and numerical evaluation of cement-fly ash-gravel pile-supported embankments over completely decomposed granite soils. Int J Geomech 19:04019048. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001430
15. **Mangraviti, V., Flessati, L., & di Prisco, C.** (2023). Geosynthetic-reinforced and pile-supported embankments: theoretical discussion of finite difference numerical analyses results. European Journal of Environmental and Civil Engineering, *27*(15), 4337–4363. https://doi.org/10.1080/19648189.2023.2190400
16. **Jumadilova, S. Zh., Khomyakov, V. A., & Kuanyshbai, A. M.** (2024). Technology for strengthening soil materials using two-component polyurethane material GEOPUR. Bulletin of QazBSQA, 1(91), 65–74. https://doi.org/10.51488/1680-080X/2024.1-05, (In Kaz.).
17. **Holt SJ, Griffiths IW, Fielder S, Garelick J, Milne C, O'Rourke R, Savill F, Payne I** (2025), "Railway embankment failure trends and monitoring – lessons learned from the Anglia route". Proceedings of the Institution of Civil Engineers - Civil Engineering, Vol. 178 No. 1 pp. 64–77, doi: https://doi.org/10.1680/jcien.24.00947
18. **Pilecka, E.; Szwarkowski,D.; Stanisz, J.; Blockus, M.** (2022), Analysis of a Landslide on a Railway Track Using Laser Scanning and FEM Numerical Modelling. Appl. Sci., 12, 7574. https://doi.org/10.3390/app12157574

19. **Su, G.; Liu, H.; Dai, G.; Chen, X.; Deng, Y. (**2023). Dynamic Analysis of a Concrete-Cored Deep Cement Mixing Pile under Horizontal Dynamic Loads. Buildings, 13,1378. https://doi.org/10.3390/buildings13061378
20. **Jianbo Fei, Yuxin Jie, Chengyu Hong, Changsuo Yang.** (2020) Comparative Analysis of Design Parameters for High-Speed Railway Earthworks in Different Countries and a Unified Definition of Embankment Substructure. The Baltic journal of road and bridge engineering 15(2). https://doi.org/10.7250/bjrbe.2020-15.476
21. **Apshikur, B., Alimkulov, M. ., Kapasov, A., Goltsev, A., & Chernavin, V.** (2024). an effective way to stop the deformation displacement of road embankments built from weak soil prone to subsidence. *kazatc bulletin*, *131*(2), 89–103. https://doi.org/10.52167/1609-1817-2024-131-2-89-103. (In Kaz.).
22. **Zhussupbekov, A., Kaliakin, V., Ashkey, Y.** (2025) et al. Static and Dynamic Testing of Precast Concrete Joint Piles Installed with Pre-drilling. Transp. Infrastruct. Geotech. 12, 274. https://doi.org/10.1007/s40515-025-00705-6. (In Kaz.).
23. **Liu, Zh., Liu, J., Li, X., Fang, J.** (2018). Experimental study on the volume and strength change of an unsaturated silty clay upon freezing. Cold Regions Science and Technology. 157. https://doi.org/10.1016/j.coldregions.2018.09.008
24. **Bosso, N.; Magelli, M.; Zampieri, N. (**2023). Dynamical Effects of the Increase of the Axle Load on European Freight Railway Vehicles. Appl. Sci., 13, 1318. https://doi.org/10.3390/app13031318
25. **Zhang, P., He, C., Shen, C., Dollevoet, R., & Li, Z.** (2024). Comprehensive validation of three-dimensional finite element modelling of wheel-rail high-frequency interaction via the V-Track test rig. Vehicle System Dynamics, 62(11), 2785–2809. https://doi.org/10.1080/00423114.2024.2304626
26. **Yajun Jiang and Sanjay Nimbalkar** (2019). Finite Element Modeling of Ballasted Rail Track Capturing Effects of Geosynthetic Inclusions. Front. Built Environ. Sec. Transportation and Transit Systems. Volume 5. https://doi.org/10.3389/fbuil.2019.00069
27. **Zhao Z and Zheng L** (2024) Influences of the geogrid-reinforced soil platform on the performance of pile-supported embankment. Front. Earth Sci. 12:1486831. https://doi.org/10.3389/feart.2024.1486831
28. **Wang, R.; Chen, G.; Xu, N.; Sun, L.; Wu, J.; Xu, G. (**2025) Impact of High Contact Stress on the Wear Behavior of U75VH Heat-Treated Rail Steels Applied for Turnouts. Metals, 15, 676. https://doi.org/10.3390/met15060676
29. **Li H, Ye Y, Zhang Z, Yu W, Zhu W. A (**2024). comparative analysis of CAD modeling approaches for design solution space exploration. Advances in Mechanical Engineering.;16(3). https://doi.org/10.1177/16878132241238089
30. **Isakhanov, E. A., Kvashnin, M. Ya., Abiev, B. A., & Alpysbayeva, Zh**. (2013). Resistance to shear of cohesionless soils under static and vibrational loading. Bulletin of QazBSQA: Design, Construction and Operation of Transport Structures, 4(83), 4–9 [Soprotivlenie sdvigu nesvyaznykh gruntov pri staticheskikh i vibratsionnykh nagruzkakh]. (In Kaz.).
31. **Kvashnin, M. Ya., Bondar, I. S., Khasenov, S. S., & Bikhozhaeva, G. S.** (2021). Determination of stresses and dynamic coefficients when testing railway overpasses. Bulletin of QazBSQA: Construction Structures and Materials, 2(80), 229–237. https://doi.org/10.51488/1680-080X/2021.2-14 [Opredelenie napryazhenii i dinamicheskikh koeffitsientov pri ispytaniyakh zheleznodorozhnykh puteprovodov].(In Kaz.).
32. **Morais J, Morais P, Santos C, Paixão A, Fortunato E. (**2022). Railway track support condition assessment-Initial developments on a vehicle-based monitoring solution through modal analysis. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit.;236(9):1058-1069. https://doi.org/10.1177/09544097211064101
33. **Lei Xu, Wanming Zhai** (2021) Vehicle–track–tunnel dynamic interaction: a finite/infinite element modelling method, Rail. Eng. Science 29(2): 109–126. https://doi.org/10.1007/s40534-021-00238-x