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RESEARCH ARTICLE

EFFECT OF STRUCTURAL PROTECTION AGAINST WATER SATURATION OF FOUNDATION SOILS ON RAILWAY EMBANKMENT STABILITY

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Abstract. *Ensuring the stability of railway embankments under high groundwater conditions is an important geotechnical challenge, as the saturation of weak foundation soils may alter their strength and deformation characteristics and lead to additional displacements of the earthwork. This study aims to numerically assess the stability and deformation behaviour of a railway embankment incorporating an integrated structural solution in which a gravel layer is positioned 0.5 m above the design high-water level and the foundation is reinforced with geosynthetic materials. Numerical modelling was performed using the finite element method in PLAXIS 2D, employing the elastoplastic Mohr-Coulomb model. Stability was evaluated using the Strength Reduction Method under both basic and special load combinations. In addition, the deformation behaviour of the embankment was analysed after 300 days of consolidation. Under the basic load combination, the calculated factor of safety was 1.47, compared with the minimum permissible value of 1.20. Under the special load combination incorporating seismic action, the factor of safety decreased to 1.10, compared with the prescribed value of 1.08. The maximum calculated foundation settlement was 0.151 m, while the maximum horizontal and vertical displacements were 0.280 m and - 0.450 m, respectively. The results demonstrate that the proposed structural configuration satisfies the adopted stability criterion under both load combinations, although the special load combination governs the available stability margin. The findings characterise the combined response of the drainage gravel layer, geosynthetic reinforcement, and foundation soils and may support the design of railway embankments under challenging hydrogeological conditions.*

Keywords: *railway embankment; soil saturation; high groundwater level; slope stability; geosynthetic materials; numerical modelling; stress-strain state.*

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НЕГІЗДІ СУҒА ҚАНЫҒУДАН КОНСТРУКЦИЯЛЫҚ ҚОРҒАУДЫҢ ТЕМІРЖОЛ ҮЙІНДІСІНІҢ ОРНЫҚТЫЛЫҒЫНА ӘСЕРІ

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Аңдатпа. *Жерасты суларының деңгейі жоғары жағдайларда теміржол үйінділерінің орнықтылығын қамтамасыз ету өзекті геотехникалық міндет болып табылады, өйткені негіздегі әлсіз топырақтардың суға қанығуы олардың беріктік және деформациялық сипаттамаларының өзгеруіне және жер төсемінің қосымша орын ауыстыруларының дамуына әкелуі мүмкін. Зерттеудің мақсаты есептік жоғары су деңгейінен 0,5 м биіктікте малтатас қабатын орналастыруды және негізді геосинтетикалық материалдармен күшейтуді көздейтін кешенді конструкциялық шешім қолданылған кездегі теміржол үйіндісінің орнықтылығы мен деформациялық күйін сандық бағалау болып табылады. Сандық модельдеу PLAXIS 2D бағдарламалық кешенінде серпімді-пластикалық Mohr–Coulomb моделін пайдалана отырып, ақырлы элементтер әдісімен орындалды. Орнықтылық жүктемелердің негізгі және ерекше үйлесімдері кезінде топырақтың беріктік сипаттамаларын төмендету әдісімен бағаланды. Сонымен қатар, 300 тәулік консолидациядан кейінгі үйіндінің деформациялық күйі талданды. Жүктемелердің негізгі үйлесімі кезінде есептік орнықтылық коэффициенті ең төмен рұқсат етілген 1,20 мәнімен салыстырғанда 1,47 болды. Сейсмикалық әсер ескерілген ерекше үйлесім кезінде орнықтылық коэффициенті нормативтік 1,08 мәнімен салыстырғанда 1,10-ға дейін төмендеді. Негіздің максималды есептік шөгуі 0,151 м, горизонталь орын ауыстыруы 0,280 м, ал вертикаль орын ауыстыруы -0,450 м болды. Зерттеу нәтижелері қарастырылған конструкциялық схеманың жүктемелердің екі үйлесімі кезінде де қабылданған орнықтылық критерийін қамтамасыз ететінін, алайда орнықтылық қоры бойынша ерекше үйлесімнің анықтаушы болып табылатынын көрсетті. Алынған нәтижелер дренаждық малтатас қабатының, геосинтетикалық күшейтудің және негіз топырақтарының бірлескен жұмысын сипаттайды және күрделі гидрогеологиялық жағдайларда теміржол үйінділерінің конструкциялық шешімдерін негіздеу кезінде пайдаланылуы мүмкін.*

Түйінді сөздер: *теміржол үйіндісі; топырақтың суға қанығуы; жерасты суларының жоғары деңгейі; беткейлердің орнықтылығы; геосинтетикалық материалдар; сандық модельдеу; кернеулі-деформацияланған күй.*

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НАУЧНАЯ СТАТЬЯ

ВЛИЯНИЕ КОНСТРУКТИВНОЙ ЗАЩИТЫ ОСНОВАНИЯ ОТ ВОДОНАСЫЩЕНИЯ НА УСТОЙЧИВОСТЬ ЖЕЛЕЗНОДОРОЖНОЙ НАСЫПИ

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Аннотация. *Обеспечение устойчивости железнодорожных насыпей в условиях высокого уровня грунтовых вод является актуальной геотехнической задачей, поскольку водонасыщение слабых грунтов основания может сопровождаться изменением их прочностных и деформационных характеристик и развитием дополнительных перемещений земляного полотна. Цель исследования заключается в численной оценке устойчивости и деформационного состояния железнодорожной насыпи при применении комплексного конструктивного решения, предусматривающего размещение галечникового слоя выше расчетного уровня высокой воды на 0,5 м и усиление основания геосинтетическими материалами. Численное моделирование выполнено методом конечных элементов в программном комплексе PLAXIS 2D с использованием упругопластической модели Mohr-Coulomb. Устойчивость оценивалась методом снижения прочностных характеристик грунта при основном и особом сочетаниях нагрузок. Дополнительно анализировалось деформационное состояние насыпи после 300 сут консолидации. При основном сочетании нагрузок расчетный коэффициент устойчивости составил 1,47 при минимально допустимом значении 1,20. При особом сочетании с учетом сейсмического воздействия коэффициент устойчивости снизился до 1,10 при нормативном значении 1,08. Максимальная расчетная осадка основания составила 0,151 м, горизонтальное смещение - 0,280 м, вертикальное перемещение-0,450 м. Установлено, что рассмотренная конструктивная схема обеспечивает выполнение принятого критерия устойчивости при обоих сочетаниях нагрузок, при этом особое сочетание является определяющим по запасу устойчивости. Полученные результаты характеризуют совместную работу дренирующего галечникового слоя, геосинтетического усиления и грунтового основания и могут быть использованы при обосновании конструктивных решений железнодорожных насыпей в сложных гидрогеологических условиях.*

Ключевые слова: *железнодорожная насыпь; водонасыщение грунтов; высокий уровень грунтовых вод; устойчивость откосов; геосинтетические материалы; численное моделирование; напряженно-деформированное состояние.*

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1 INTRODUCTION

The reliability and durability of railway earthworks are largely governed by the engineering geological and hydrogeological conditions of the foundation. The construction and operation of embankments on weak and deformable soils present particular challenges, as variations in moisture content, groundwater level, and applied loads may lead to differential settlement, horizontal displacements, and reduced slope stability. Studies of earth structures constructed on weak foundations indicate that ensuring their stability requires an integrated consideration of soil properties, embankment geometry, hydrogeological conditions, and the adopted reinforcement techniques [1]. For railway infrastructure, this issue is particularly important because of the long-term effects of train loading and the stringent requirements imposed on permissible earthwork deformations [2; 3].

Hydrogeological conditions are among the key factors governing the stress–strain behaviour of soil foundations. A rise in groundwater level and an increase in the degree of soil saturation may alter the mechanical behaviour of soils and, consequently, the response of the ‘foundation-embankment’ system. Finite element modelling of unsaturated soil behaviour confirms the need to account for changes in the hydromechanical state of the soil medium in geotechnical analyses [4]. This factor is particularly important for railway embankments subjected to periodic or seasonal inundation. Laboratory investigations and numerical modelling of such structures have demonstrated that seasonal soil saturation significantly affects their hydromechanical behaviour and that the effectiveness of reinforcement should be assessed with due consideration of variations in the groundwater regime of the foundation [5]. These findings highlight the need to consider measures for protection against water saturation and structural reinforcement as interrelated components of an integrated engineering solution.

One widely adopted method for improving the performance of railway earthworks constructed on weak foundations is the use of geosynthetic materials. Their application enables reinforcement of the soil mass, redistribution of induced stresses, and restriction of deformation development. The fundamental principles of geosynthetic design and the mechanisms governing soil-geosynthetic interaction have been extensively described in established studies and design guidelines [6; 7]. In railway infrastructure, geosynthetic materials are used to stabilise sub-ballast layers and track foundations, increase bearing capacity, and improve the service performance of the structure [8; 9]. The effectiveness of geosynthetic reinforcement for slopes and earth structures has also been demonstrated in studies examining various structural solutions for transport infrastructure [10].

Previous investigations of the stress–strain behaviour of railway earthworks conducted with the participation of the present authors have demonstrated the feasibility of geosynthetic reinforcement for embankments constructed on weak foundations. Numerical analysis enables the redistribution of stresses and deformations within a reinforced system to be evaluated while accounting for the interaction between foundation soils and geosynthetic elements [11]. For multi-track railway sections constructed on weak foundations, computational schemes incorporating geogrid reinforcement have also been investigated to assess the stress–strain response of the structure under different operating conditions [12]. Further development of this research involved the application of the finite element method to establish computational algorithms for evaluating the stress–strain state of railway earthworks [13] and to investigate the deformability of railway embankments [14]. Collectively, these studies provide a methodological basis for progressing from the assessment of individual reinforcement elements towards an integrated analysis of the ‘foundation–embankment’ system.

For the quantitative assessment of earth-structure stability, numerical methods based on the finite element method have become widely established. Unlike approaches based on a predefined potential slip surface, the Strength Reduction Method (SRM) progressively reduces the soil strength parameters until the numerical model reaches a limit state. The foundations for applying this procedure to finite element slope stability analysis were established by Matsui and San [15] and Griffiths and Lane [16]. Subsequent studies have confirmed the applicability of the SRM to a range of geometric and engineering geological conditions and have focused on improving the computational

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procedure and the analysis of failure mechanisms [17; 19]. Finite element modelling applied directly to embankments constructed on weak clay foundations has also demonstrated its ability to reproduce their stress-strain response and to analyse the development of deformations during construction and subsequent operation [20].

Modern finite element software enables the simultaneous consideration of embankment geometry, construction sequence, the physical and mechanical properties of engineering geological units, groundwater level, applied loads, and the response of reinforcement elements. Different constitutive models may be employed to represent the soil mass, while stability can be evaluated using a strength reduction procedure [21]. This approach is particularly suitable for the present problem because it enables not only the assessment of the limit state in terms of stability but also the evaluation of foundation settlement and horizontal and vertical displacements within the soil mass. The applicability of finite element software to geotechnical engineering problems has also been demonstrated in previous numerical studies [20; 22].

Nevertheless, most studies of reinforced railway embankments have focused primarily either on the mechanical effects of geosynthetic reinforcement or on the stability and deformation behaviour of the foundation. Under high groundwater conditions, another important aspect is the interaction between the position of the saturated zone and the structural arrangement of drainage and reinforcement layers. Under such conditions, geosynthetic materials should therefore be considered not as an isolated reinforcement measure but as part of an integrated system for protecting the foundation against water saturation, including the placement of a coarse-grained filtering layer above the design high-water level. This approach is intended both to provide the required embankment stability and to reduce the adverse effects of soil saturation on foundation performance.

Accordingly, the aim of this study is to quantitatively evaluate the stability and deformation behaviour of a railway embankment incorporating an integrated structural solution comprising a gravel layer positioned 0.5 m above the design high-water level and geosynthetic reinforcement of the foundation. The scientific novelty of the study lies in the integrated numerical assessment of this structural configuration within a single finite element model, considering both stability under basic and special load combinations, including seismic action, and deformation behaviour after 300 days of consolidation. The principal new result is the quantitative demonstration that the transition from the basic to the special load combination reduces the factor of safety from 1.47 to 1.10, corresponding to a decrease of approximately 25.2%, while the relative margin above the minimum permissible value decreases from 22.5% to approximately 1.9%. In addition, the governing potential failure zone shifts from the lower part of the embankment slope under the basic load combination to the upper part under the special load combination. The deformation analysis further establishes maximum values of foundation settlement, horizontal displacement, and vertical displacement of 0.151, 0.280, and -0.450 m, respectively, after 300 days of consolidation. These results provide an integrated characterisation of the stability and deformation response of the ‘soil foundation-gravel layer–geosynthetic reinforcement–railway embankment’ system under the investigated hydrogeological and loading conditions.

2 MATERIALS AND METHODS

The study was conducted for a railway embankment constructed under challenging engineering geological and hydrogeological conditions characterised by deformable foundation soils and a high design water level. The investigated structural solution comprised an embankment with a gravel layer positioned 0.5 m above the design high-water level and geosynthetic reinforcement incorporated at the foundation level. This solution was selected to simultaneously mitigate the adverse effects of soil saturation on the foundation soils and ensure the required stability and deformation performance of the railway earthwork. The need to consider both the groundwater regime and the mechanical response of a reinforced foundation is supported by previous studies of railway embankments subjected to seasonal inundation [5].

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The numerical model comprises the soil foundation, railway embankment body, gravel layer, track superstructure, and geosynthetic reinforcement system. The gravel layer is positioned 0.5 m above the design high-water level, while the geosynthetic elements are incorporated at the embankment foundation and within the sub-ballast zone. The adopted numerical model and the arrangement of the principal structural elements are presented in Figure 1.

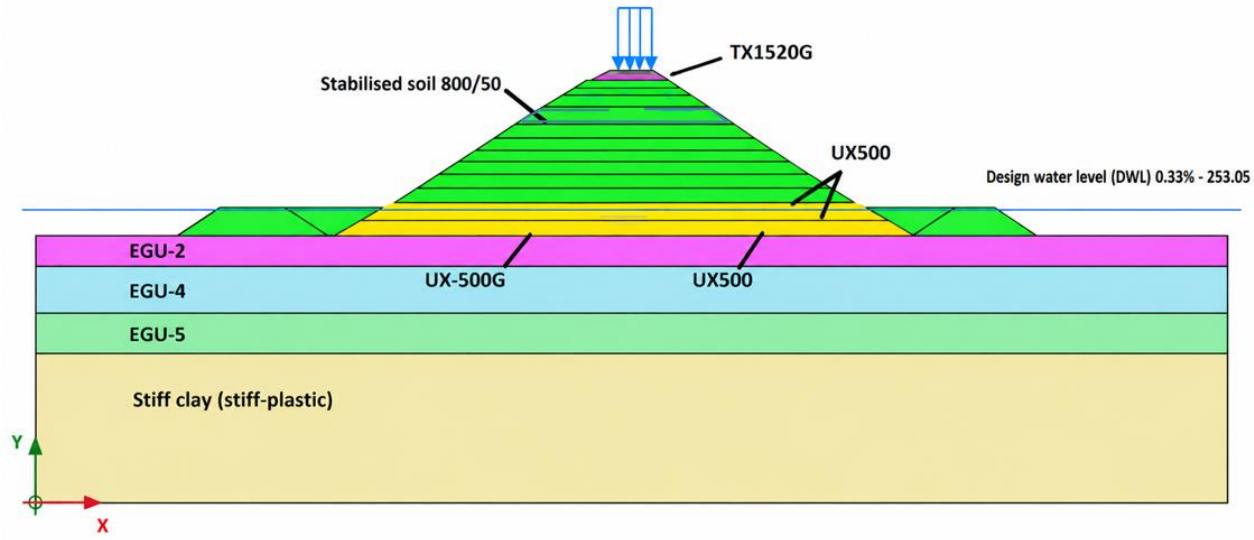


Figure 1 – Numerical model of the railway embankment with the gravel layer positioned above the design high-water level and the foundation reinforced with geosynthetic materials [Authors' material]

The numerical investigation was conducted using the finite element method in the PLAXIS 2D software package. Finite element analysis enables the heterogeneity of the soil foundation, the construction sequence, and changes in the stress–strain state of the soil mass at individual calculation stages to be taken into account. The capabilities of the finite element method for modelling embankments on weak clay foundations have been demonstrated in [20], while the principal aspects of implementing soil constitutive models in PLAXIS 2D are described in the software developer's manual [21]. The finite element approach was also previously employed by the authors to develop an algorithm for analysing the stress-strain state of railway earthworks [13].

The computational domain was defined with consideration of the embankment geometry and the stratification of the soil foundation. The analysis was performed in stages, including the generation of the initial stress state of the soil mass, construction of the embankment, activation of structural and geosynthetic elements, application of operational loads, and subsequent assessment of stability and deformation behaviour. Staged modelling enables the redistribution of stresses between the soil foundation, embankment body, and reinforcement elements to be taken into account as the numerical model is progressively developed.

The mechanical behaviour of the soils was represented using the elastoplastic Mohr-Coulomb model implemented in PLAXIS 2D [21]. The principal input parameters were cohesion c, internal friction angle φ, deformation modulus E, soil density ρ, and coefficient of permeability K_f. These parameters were used to characterise the strength and deformation properties of the individual engineering geological units (EGUs) and subsequently to evaluate stability using the Strength Reduction Method. The physical and mechanical properties of the soils adopted in the numerical model are presented in Table 1.

Table 1 – Physical and mechanical properties of the soils adopted in the numerical model

№	Soil	Cohesion (c), kPa	Internal friction angle (φ),	Deformation modulus (E), MPa	Soil density (ρ), g/cm³	Coefficient of permeability (K_f), m/day
1	Sandy loam embankment fill	20	15	7	1.80	0.46

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2	Gravel embankment fill	23	29	38	1.99	28
3	EGU-2 – soft-plastic and flow-plastic loam	9	7	3.2	2.00	0.46
4	EGU-4 – plastic and flow-plastic sandy loam	4	11	3.5	1.93	0.63
5	EGU-5 – fine sand	0	28	13.0	1.86	4.55

The shear strength of the soil within the adopted model is defined by the relationship between the normal stress, internal friction angle, and cohesion [21]:

$$\tau = \sigma tan\varphi + c \quad (1)$$

where τ is the shear strength of the soil, kPa;

σ is the effective normal stress, kPa;

φ is the internal friction angle, °;

c is the soil cohesion, kPa.

The stability of the railway embankment was assessed using the Strength Reduction Method (SRM). The method is based on the progressive reduction of the soil strength parameters c and $tan\varphi$ until the soil mass reaches a limit state. The fundamental principles of finite element stability analysis using strength reduction are presented in [15; 16]. Further developments of this method for various numerical configurations and soil conditions have been reported in [17; 19]. In PLAXIS 2D, this approach is implemented using the *Phi-c reduction* procedure [21].

The calculated factor of safety was compared with the minimum permissible value defined by the following condition:

$$K_s \geq \frac{\gamma_n \gamma_{lc}}{\gamma_c} \quad (2)$$

where K_s is the calculated factor of safety;

γ_n is the reliability factor related to the intended purpose of the structure;

γ_{lc} is the load combination factor; and γ_c is the working-condition factor.

For the adopted numerical model, the minimum permissible factor of safety was $K_{s,n} = 1.20$ for the basic load combination and $K_{s,n} = 1.08$ for the special load combination. These values were subsequently used as acceptance criteria for evaluating the numerical modelling results.

The numerical model incorporated permanent and variable loads from the track superstructure and rolling stock, while seismic action was additionally considered for the special load combination. The principal loads and actions adopted in the numerical modelling are presented in Table 2**.** The load from the track superstructure was 17 kPa, and the train load was 90 kPa for a design axle load of 295 kN. For the special load combination, a design seismic intensity of 8 points was considered, with horizontal and vertical accelerations of $a_g = 0.34g$ and $a_{gv} = 0.24g$, respectively.

Table 2 – Design loads and actions

№	Load or action	Design value
1	Track superstructure	17 kPa
2	Train load	90 kPa
3	Design axle load	295 kN
4	Seismic intensity	8 points
5	Design horizontal acceleration (a_g)	$0.34g$
6	Design vertical acceleration (a_{gv})	$0.24g$

In addition to stability, the deformation behaviour of the ‘foundation–embankment’ system was assessed. The analysis included the determination of foundation settlement and horizontal and vertical displacements of the soil mass. Such an integrated assessment is necessary because satisfying the stability criterion alone does not fully characterise the deformation performance of a railway embankment under service conditions. Numerical studies of embankments on weak foundations also

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demonstrate the importance of jointly analysing the stress–strain state and the development of settlement [20]. The deformability of railway embankments was previously investigated by the authors in [14], while changes in the stress–strain state of the active zone of railway earthworks associated with increased wagon axle loads were examined in [23].

Following completion of the construction stage, a consolidation period of 300 days was simulated. The resulting settlement and displacement fields were then determined for the basic load combination. These values were used for the quantitative assessment of the deformation behaviour of the adopted structural configuration.

Thus, the developed numerical model enables the sequential assessment of two groups of parameters: the factor of safety K_s under the basic and special load combinations, and the deformation parameters following the consolidation period. This approach enables the adopted structural solution to be evaluated not only in terms of ultimate stability but also with regard to the in-service deformation behaviour of the railway embankment.

3 RESULTS AND DISCUSSION

Numerical modelling was used to assess the stability and deformation behaviour of the railway embankment incorporating the adopted structural solution, which comprised a gravel layer positioned above the design high-water level and geosynthetic reinforcement of the foundation. Stability was evaluated for the basic and special load combinations by analysing the developed limit-state zones and the corresponding factor of safety, K_s.

Under the basic load combination, the potential failure surface developed predominantly within the embankment slope. The calculated factor of safety was K_s = 1.47, exceeding the minimum permissible value of $K_{s,n}$ = 1.20. The calculated position of the potential failure surface under the basic load combination is shown in Figure 2. The calculated factor of safety exceeds the minimum permissible value by 0.27, or 22.5%, confirming that the adopted stability criterion is satisfied.

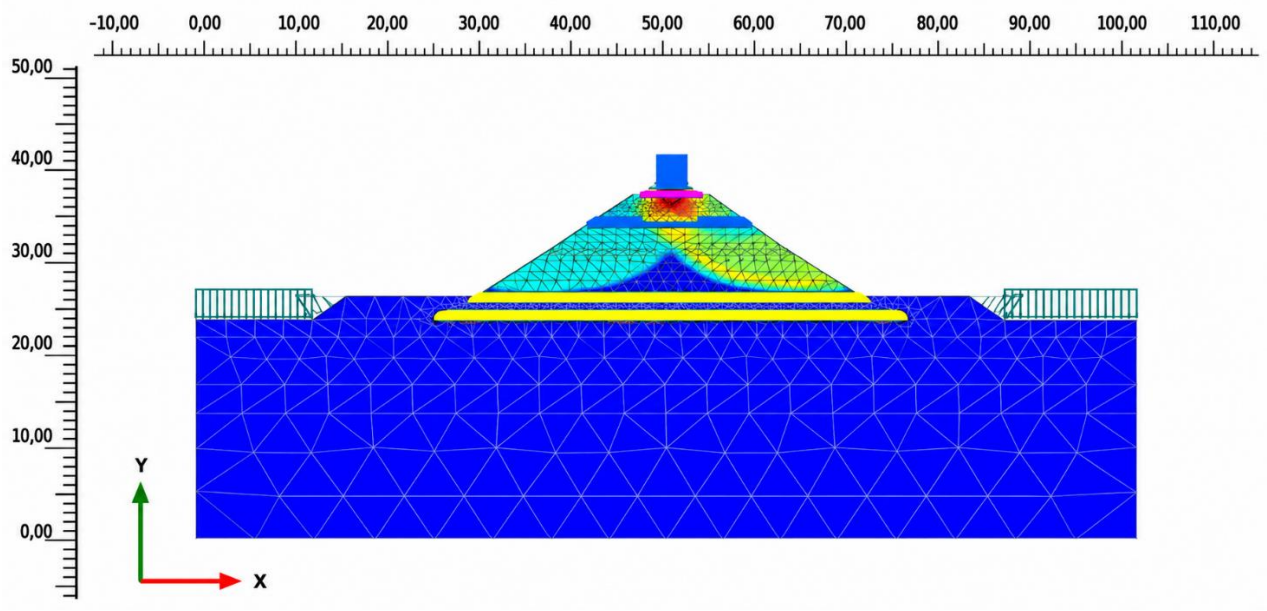


Figure 2 – Calculated position of the potential failure surface of the railway embankment under the basic load combination [Authors' material]

Under the special load combination incorporating seismic action, the calculated conditions become less favourable. The factor of safety decreases to K_s = 1.10 but remains above the minimum permissible value of $K_{s,n}$ = 1.08. The development of the potential failure surface under the special load combination is shown in Figure 3. In contrast to the basic load combination, for which the critical

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failure surface develops within the lower part of the embankment slope, under the special load combination the governing failure surface develops within the upper part of the slope. Despite the reduced stability margin, the condition $K_s \geq K_{s,n}$ remains satisfied.

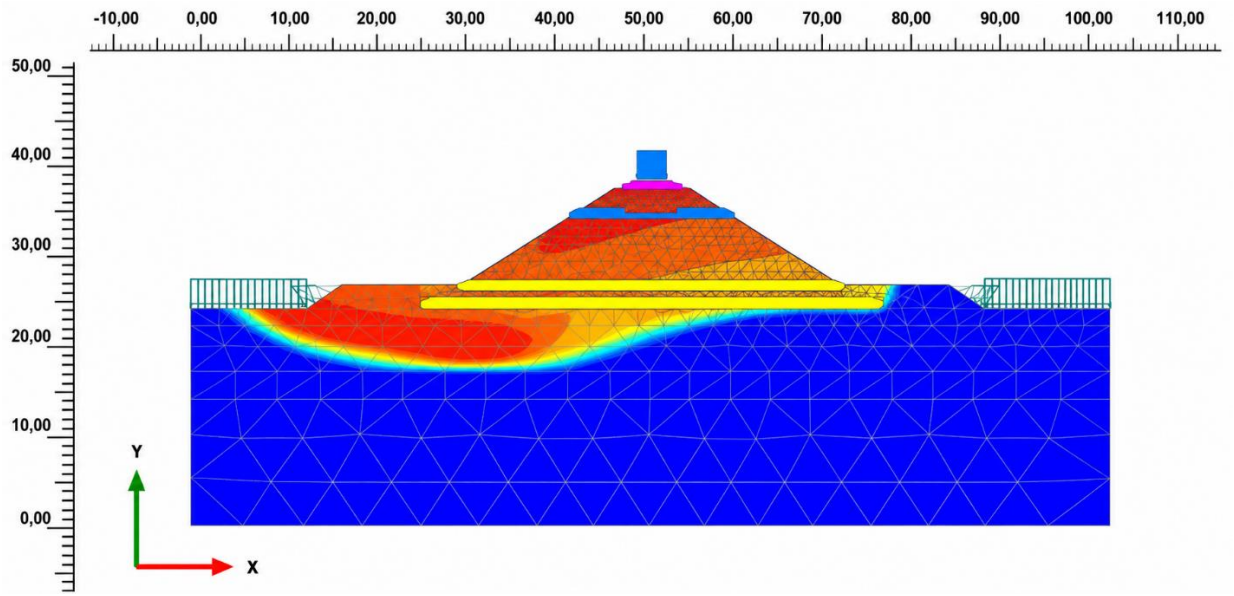


Figure 3 – Calculated position of the potential failure surface of the railway embankment under the special load combination incorporating seismic action [Authors' material]

A comparison of the two numerical cases demonstrates that the special load combination has a significant effect on the stability margin of the embankment. When transitioning from the basic to the special load combination, the factor of safety decreases from 1.47 to 1.10, corresponding to a reduction of approximately 25.2%. At the same time, the margin between the calculated and minimum permissible values decreases from 0.27 to 0.02. The calculated and minimum permissible factors of safety for the considered load combinations are summarised in Table 3.

Table 3 – Calculated factors of safety for the railway embankment

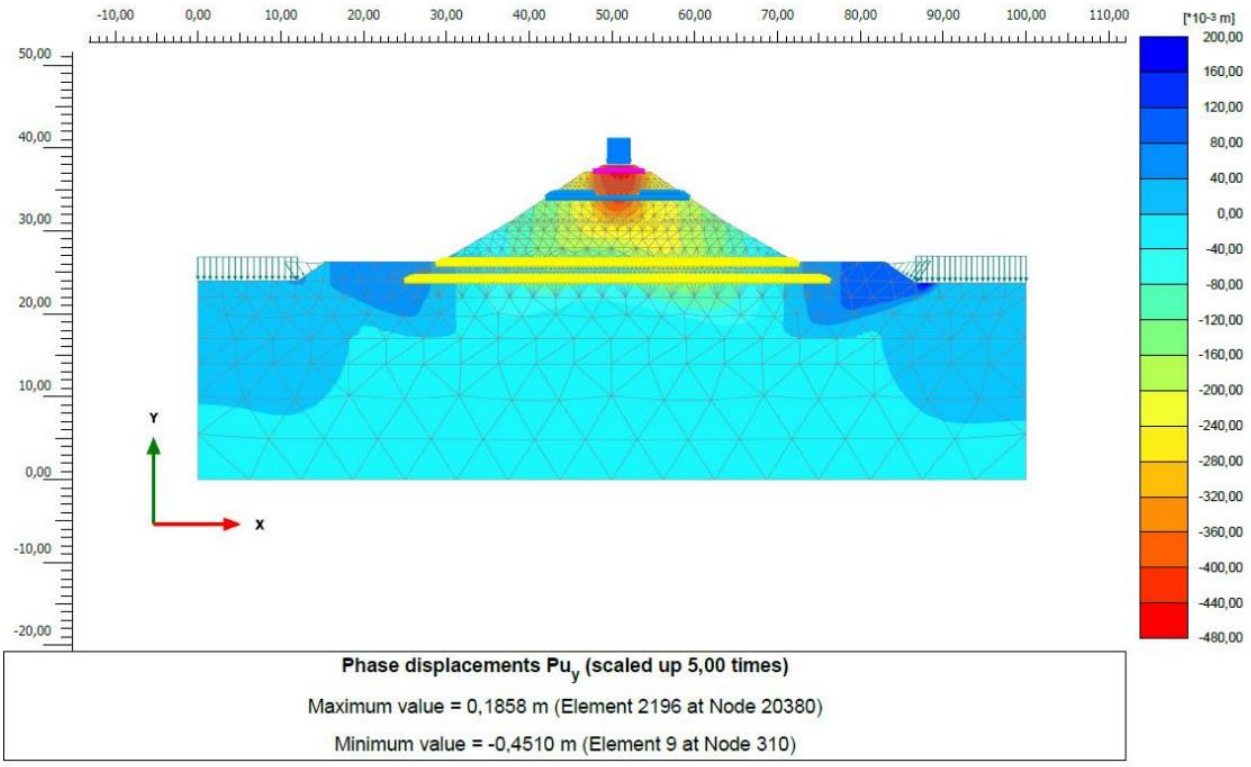
№	Load combination	K_s	$K_{s,n}$	Margin, $K_s - K_{s,n}$	Stability assessment
1	Basic	1.47	1.20	0.27	Stable
2	Special, incorporating seismic action	1.10	1.08	0.02	Stable

A comparison of the results shows that, under the basic load combination, the calculated factor of safety exceeds the minimum permissible value by 22.5%, whereas under the special load combination the relative stability margin is only approximately 1.9%. Therefore, the special load combination incorporating seismic action is the governing case for assessing the stability of the considered structural configuration.

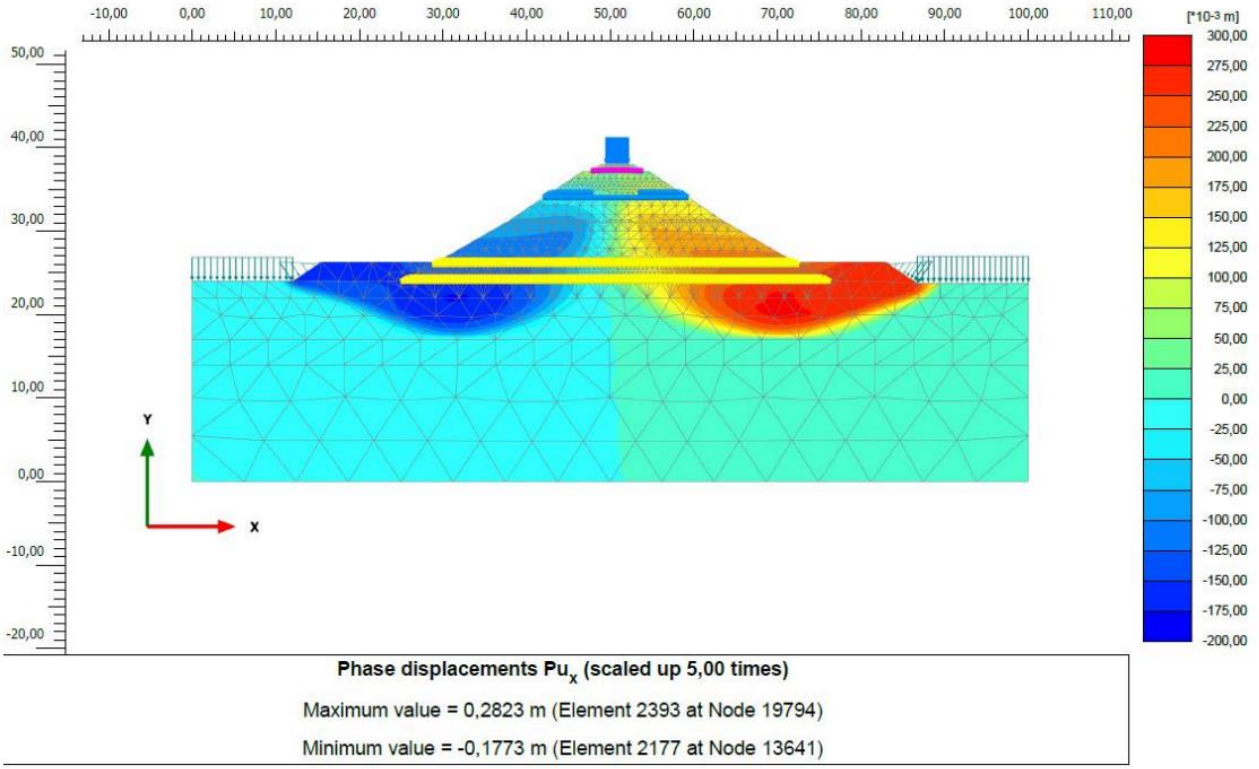
3.1 Deformation behaviour of the embankment

In addition to ultimate stability, the deformation behaviour of the 'foundation-embankment' system was assessed. Following completion of the construction stage, a consolidation period of 300 days was considered. At the end of this period, foundation settlement and horizontal and vertical displacements of the soil mass were determined. The distribution of the calculated deformations after 300 days of consolidation is presented in Figure 4.

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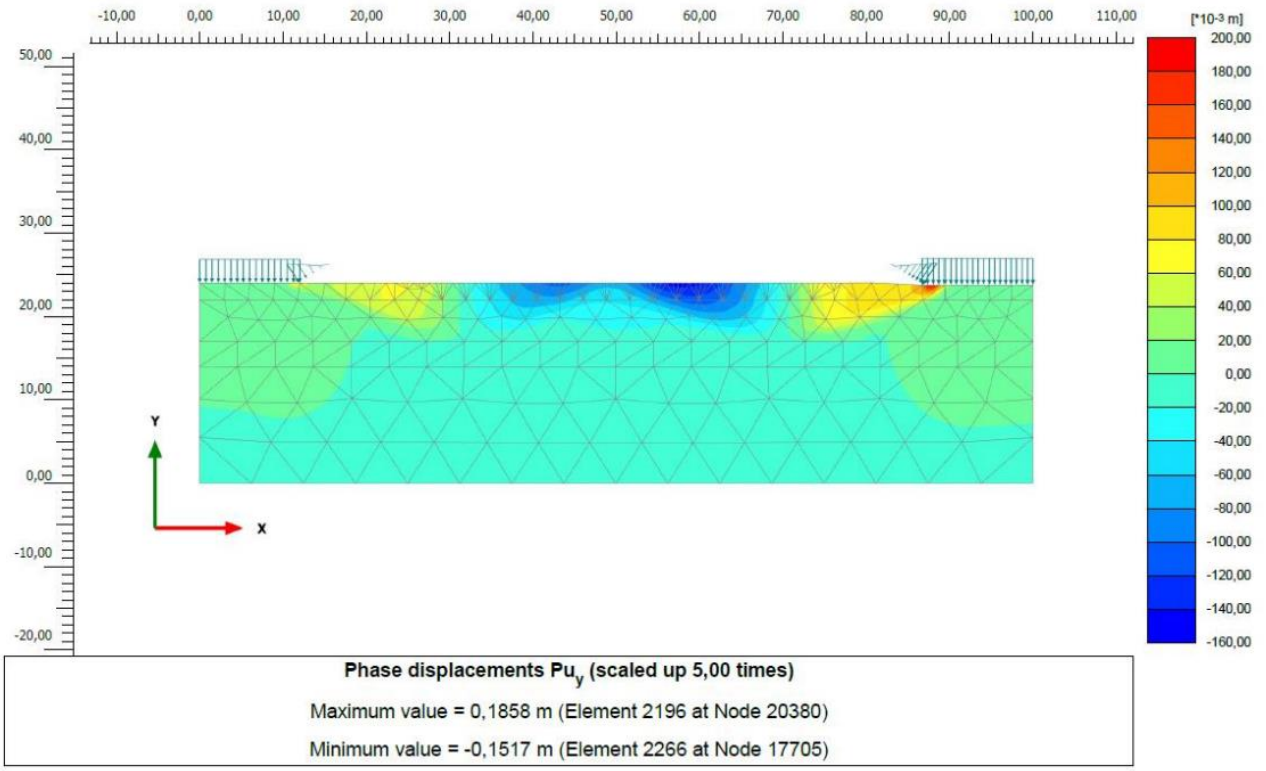


(a)



(b)

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(c)

Figure 4 – Deformation behaviour of the railway embankment after 300 days of consolidation: (a) foundation settlement; (b) horizontal displacements; (c) vertical displacements [Authors' material]

The numerical modelling results indicate that the maximum calculated foundation settlement was 0.151 m. The maximum horizontal displacement reached 0.280 m, while the maximum vertical displacement was -0.450 m. The maximum calculated deformation values are summarised in Table 4.

Table 4 – Maximum calculated deformation values of the railway embankment after 300 days of consolidation

№	Calculated parameter	Maximum value, m
1	Foundation settlement	0.151
2	Horizontal displacement	0.280
3	Vertical displacement	−0.450

The results indicate that the deformation behaviour of the structure is characterised by the development of both vertical and horizontal displacements within the soil mass. After 300 days of consolidation, the maximum calculated foundation settlement was 0.151 m, the maximum horizontal displacement was 0.280 m, and the maximum vertical displacement was − 0.450 m. The largest absolute value was obtained for the vertical displacement. The spatial distribution of these deformations is presented in Figure 4, while their quantitative comparison is shown in Figure 5.

For an integrated presentation of the numerical modelling results, the calculated factors of safety were compared with the corresponding minimum permissible values, while the deformation results were compared in terms of the maximum displacements after 300 days of consolidation (Figure 5). Under the basic load combination, the factor of safety was K_s = 1.47 compared with $K_{s,n}$ = 1.20, corresponding to a margin of 22.5% above the minimum permissible level. Under the special load combination incorporating seismic action, K_s decreased to 1.10 compared with $K_{s,n}$ = 1.08, reducing the relative stability margin to 1.9%. The deformation analysis showed maximum values ranging from a foundation settlement of 0.151 m to a horizontal displacement of 0.280 m and an

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absolute vertical displacement of 0.450 m. Thus, the integrated comparison confirms the need for a combined assessment of the ultimate stability and deformation behaviour of the railway embankment.

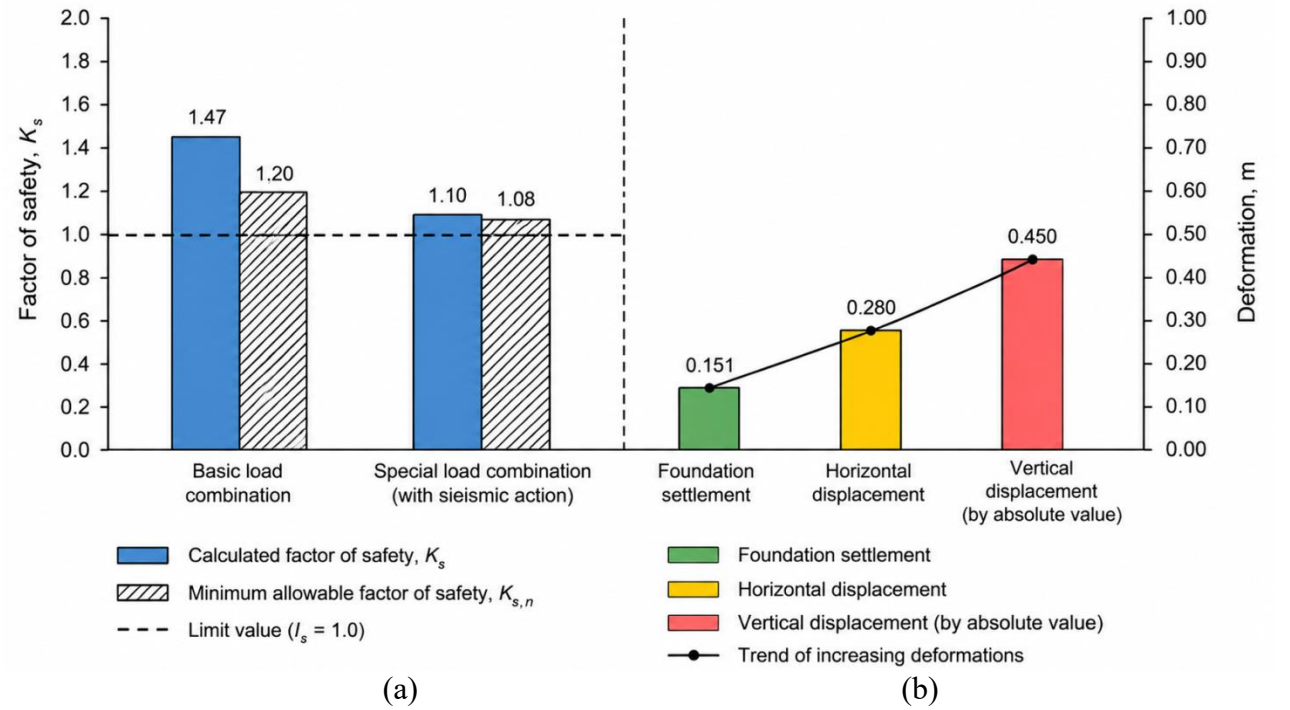


Figure 5 – Integrated assessment of the numerical modelling results for the railway embankment: (a) comparison of the calculated and minimum permissible factors of safety under the basic and special load combinations; (b) maximum calculated deformations after 300 days of consolidation [Authors' material]

Taken together, the results demonstrate that the adopted structural solution satisfies the stability criterion under both load combinations. However, the special load combination incorporating seismic action governs the stability margin. At the same time, the calculated settlements and displacements indicate that stability and deformation behaviour should be considered as complementary criteria when assessing the performance of the 'foundation-embankment' system.

The results demonstrate that the stability of the railway embankment is governed by the combined effects of the hydrogeological conditions, the adopted foundation configuration, and the design load combination. Under the basic load combination, the factor of safety was K_s = 1.47 compared with the minimum permissible value of $K_{s,n}$ = 1.20, whereas under the special load combination incorporating seismic action it decreased to K_s = 1.10 compared with $K_{s,n}$ = 1.08. Thus, the transition from the basic to the special load combination resulted in a reduction of approximately 25.2% in the calculated factor of safety. Although the adopted stability criterion was satisfied in both cases, under seismic action the relative margin above the minimum permissible value was only approximately 1.9%. The special load combination can therefore be regarded as the governing case for assessing the stability of the investigated structural configuration.

This trend is consistent with the general understanding of the behaviour of earth embankments constructed on weak foundations. The performance of such structures is governed not only by the strength and deformation properties of the soils but also by hydrogeological conditions, embankment geometry, and the nature of external actions [1]. The groundwater regime is particularly important for railway embankments subjected to periodic or seasonal inundation. Experimental investigations and numerical modelling of the hydromechanical behaviour of railway embankments under seasonal soil saturation have demonstrated the need to consider both variations in the groundwater regime and the response of reinforcement elements when assessing structural performance [5].

A key component of the investigated structural configuration is the position of the gravel layer relative to the design high-water level. In the adopted numerical model, the gravel layer is positioned

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0.5 m above the design high-water level. This arrangement provides a coarse-grained zone beneath the embankment with substantially greater permeability than the weak foundation soils. According to the physical and mechanical properties presented in Table 1, the coefficient of permeability of the gravel embankment fill is K_f = 28 m/day, whereas that of the soft-plastic and flow-plastic loam of EGU-2 is K_f = 0.46 m/day. The difference is more than 60-fold, indicating a fundamental contrast in the permeability of these materials.

EGU-2 is characterised not only by low permeability but also by comparatively low strength and deformation parameters: the cohesion is c = 9 kPa, the internal friction angle is φ = 7°, and the deformation modulus is E = 3.2 MPa (Table 1). Consequently, changes in the hydrogeological state of this layer may have a significant influence on the response of the 'foundation-embankment' system. Finite element studies of unsaturated soils have similarly demonstrated the importance of accounting for the hydromechanical state of the soil medium in geotechnical modelling [4], while the influence of seasonal soil saturation on railway embankments has been confirmed through laboratory investigations and numerical modelling [5]. A comparable emphasis on the combined influence of soil and water conditions was reported by Abu et al. [24], who used PLAXIS 2D with the Mohr–Coulomb model to analyse a soil-structure system under combined soil and water loading, explicitly accounting for soil stratification and hydrostatic pressure. Although the structure investigated in [24] differs from a railway embankment, the study similarly demonstrates the importance of incorporating hydrological conditions into finite element assessments of geotechnical systems.

Geosynthetic reinforcement constitutes the second component of the integrated structural solution considered in this study. The performance of geosynthetic materials is governed by the interaction between the reinforcement and the surrounding soil mass, the redistribution of induced stresses, and the restriction of deformation development, which form the fundamental principles of reinforced-soil design [6; 7]. For railway applications, the effectiveness of geosynthetic materials in stabilising the foundation and sub-ballast layers has been investigated in [8; 9], while previous numerical studies by the authors have demonstrated their applicability to the stress–strain analysis of railway earthworks constructed on weak foundations [11; 12]. These observations are consistent with recent studies published in the Bulletin of the Kazakh Leading Academy of Architecture and Civil Engineering. Apshikur et al. [25] reported that integrated strengthening measures for railway embankments on weak foundations reduced vertical settlements by 35-40% and horizontal displacements by up to 25%. Tursynbayev et al. [26] likewise demonstrated that geosynthetic reinforcement of clay soils improves foundation performance through increased bearing capacity and reduced deformation. Experimental investigations by Kanatova et al. [27] further confirmed the influence of geosynthetic reinforcement on soil strength under triaxial compression and single-plane shear conditions. Taken together, these studies support the broader conclusion that reinforcement of weak soils can improve both strength and deformation performance. The present results complement these findings by considering geosynthetic reinforcement as part of an integrated configuration that also incorporates the position of a drainage gravel layer relative to the design high-water level.

However, the results of the present study require a clear distinction between the outcomes directly established by the numerical analysis and their engineering interpretation. In the investigated model, the gravel layer and geosynthetic elements form part of a single numerical configuration. Separate cases without geosynthetic reinforcement or without raising the gravel layer relative to the design high-water level were not analysed. Therefore, the obtained values of K_s = 1.47 and K_s = 1.10 cannot be quantitatively attributed exclusively either to the gravel layer or to the geosynthetic reinforcement. Instead, they characterise the combined response of the 'soil foundation-gravel layer-geosynthetic reinforcement–railway embankment' system.

An important finding is the change in the failure mechanism when transitioning from the basic to the special load combination. As shown in Figure 2, under the basic load combination the critical zone is predominantly associated with the lower part of the embankment slope. When seismic action is incorporated, the position of the potential failure surface changes, and the upper part of the slope becomes the governing critical zone (Figure 3). At the same time, the factor of safety decreases by 25.2%. This indicates that assessing the structural configuration solely under the basic operational

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load combination would be insufficient to identify the most unfavourable design condition. The importance of explicitly accounting for dynamic actions in geotechnical modelling is also reflected in recent studies published in the Bulletin of the Kazakh Leading Academy of Architecture and Civil Engineering. Tursynkozha et al. [28] used PLAXIS 2D to investigate the propagation of railway-induced vibrations through layered soils and demonstrated that the dynamic response depends on the geotechnical conditions and wave-propagation characteristics. Shadkam et al. [29] examined seismic deformation using the Mohr-Coulomb and Hardening Soil Small constitutive models, highlighting the influence of both dynamic loading and the adopted soil model on calculated deformation behaviour. Although the loading mechanisms considered in these studies differ from the seismic stability analysis performed here, they support the need to incorporate dynamic actions explicitly when evaluating soil–structure response.

The observed development of the potential failure surface is consistent with the capabilities of the Strength Reduction Method. Unlike methods in which the location of the slip surface is predefined, the finite element Strength Reduction Method allows the critical zone to develop directly during the progressive reduction of the soil strength parameters [15; 16]. Subsequent developments of this approach have confirmed its applicability to slopes with different configurations and to the investigation of mechanisms leading to the limit state [17; 19]. Therefore, the change in the position of the critical zone observed in Figures 2 and 3 represents an important numerical modelling result rather than merely a visual representation of the calculated factor of safety.

In addition to stability, the deformation analysis provides important information on structural performance. After 300 days of consolidation, the maximum calculated foundation settlement was 0.151 m, the maximum horizontal displacement was 0.280 m, and the maximum vertical displacement was -0.450 m (Table 4). The distributions of the corresponding deformations are shown in Figure 4. Thus, satisfying the stability criterion does not imply the absence of appreciable deformations within the soil mass, highlighting the need to consider both ultimate stability and the stress-strain behaviour of the structure. This interpretation is consistent with finite element studies of embankments constructed on weak clay foundations, in which settlements and displacements are analysed alongside the overall structural response [20]. It is also consistent with the railway-embankment study by Apshikur et al. [25], in which deformation indicators were used to quantify the effectiveness of different foundation-strengthening measures. Previous studies by the present authors have similarly addressed the deformability of railway embankments [14] and changes in the stress-strain state of the active zone of railway earthworks associated with increased axle loading [23]. Taken together, these findings support the use of deformation parameters as an independent group of criteria when evaluating the performance of railway earthworks.

When interpreting the absolute displacement values, the assumptions adopted in the numerical analysis should be taken into account. The elastoplastic Mohr-Coulomb model represents the soil medium using a limited set of parameters and does not fully reproduce the nonlinear stress-dependent stiffness of soils [21]. The relevance of constitutive-model selection under dynamic conditions has also been demonstrated by Shadkam et al. [29], who compared deformation predictions obtained using the Mohr-Coulomb and Hardening Soil Small models under seismic loading. Their analysis indicates that the adopted constitutive formulation can influence the calculated deformation response. Consequently, the displacement values obtained in the present study should be interpreted as results specific to the adopted Mohr-Coulomb model and used primarily to assess the behaviour of the investigated structural configuration under the specified engineering geological conditions.

Furthermore, the present study represents a specific design high-water level and an adopted elevation of the gravel layer. This limits the direct generalisation of the quantitative results to sites with different hydrogeological conditions. A more comprehensive assessment of the influence of structural foundation protection would require parametric modelling of several groundwater levels, gravel-layer elevations, and geosynthetic reinforcement configurations. Comparison of these alternatives would enable the contributions of individual factors to be quantitatively distinguished and the sensitivity of the factor of safety, settlement, and displacements to changes in the structural parameters to be determined. This direction is also consistent with the need for further development

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of reinforced-foundation design methods and combined reinforcement technologies identified in recent studies [26].

Overall, the results demonstrate that the investigated integrated structural configuration satisfies the adopted stability criterion under both the basic and special load combinations, although seismic action substantially reduces the stability margin. At the same time, the calculated settlements and displacements confirm that the railway embankment should be assessed not only in terms of the factor of safety, K_s, but also with respect to its deformation behaviour. In the present configuration, the position of the gravel layer relative to the design high-water level and the geosynthetic reinforcement should be regarded as components of an integrated system for foundation protection and reinforcement; quantitatively separating their individual effects will require further comparative numerical modelling.

4 CONCLUSIONS

A numerical investigation of the stability and deformation behaviour of a railway embankment under a high design water level was conducted. An integrated structural solution incorporating a gravel layer positioned 0.5 m above the design high-water level and geosynthetic reinforcement of the foundation was considered. Based on the finite element modelling results, the following conclusions can be drawn.

1. Under the basic load combination, the calculated factor of safety of the railway embankment was K_s = 1.47, compared with the minimum permissible value of $K_{s,n}$ = 1.20. The calculated value exceeded the minimum permissible value by 0.27, or 22.5%, confirming that the adopted stability criterion was satisfied.
2. Incorporating the special load combination with seismic action reduced the factor of safety to K_s = 1.10, compared with the minimum permissible value of $K_{s,n}$ = 1.08. Relative to the basic load combination, K_s decreased by approximately 25.2%, while the relative margin above the minimum permissible level was approximately 1.9%. Therefore, the special load combination represents the governing case for assessing the stability of the investigated structural configuration.
3. The load combination affected not only the magnitude of the factor of safety but also the position of the potential failure surface. Under the basic load combination, the critical zone developed predominantly within the lower part of the embankment slope, whereas under the special load combination incorporating seismic action, the upper part of the slope became the governing critical zone. This finding confirms the importance of considering different load combinations when assessing the ultimate limit state of railway earthworks.
4. The deformation analysis after 300 days of consolidation indicated a maximum foundation settlement of 0.151 m, a maximum horizontal displacement of 0.280 m, and a maximum vertical displacement of -0.450 m. The occurrence of these displacements despite satisfaction of the stability criterion demonstrates the need to assess both the factor of safety and deformation parameters when evaluating railway embankment performance.
5. The position of the gravel layer relative to the design high-water level is an important component of the investigated structural configuration. The coefficient of permeability of the gravel material was 28 m/day, compared with 0.46 m/day for the weak soft-plastic and flow-plastic loam of the foundation. This substantial difference in permeability supports the use of coarse-grained material in the investigated configuration under high groundwater conditions.
6. The calculated stability and deformation parameters characterise the combined response of the ‘soil foundation-gravel layer-geosynthetic reinforcement-railway embankment’ system. As separate numerical cases without raising the gravel layer or without geosynthetic reinforcement were not considered in the present study, the calculated effects should not be quantitatively attributed exclusively to either component.
7. Further research should focus on parametric modelling of different groundwater levels, gravel-layer elevations, and geosynthetic reinforcement configurations. Such comparative analyses would enable the effects of hydrogeological and structural factors to be quantitatively distinguished

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and facilitate the identification of rational parameters for the protection and reinforcement of railway embankments under challenging engineering geological conditions.

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The authors state that there is no conflict of interest.

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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.

AUTHOR CONTRIBUTIONS

Baitak Apshikur – conceptualisation, methodology, investigation, formal analysis, data curation, writing – original draft preparation.
Murat Alimkulov – scientific supervision, methodology, validation, writing – review and editing.
Asset Belgimbayev – methodology, validation, interpretation of results, writing – review and editing.
Kuntuqan Doshtaev – investigation, data curation, visualisation.
Ainur Kutzhanova – literature review, investigation, formal analysis.
Kuvandik Lesov – methodology, validation, interpretation of results.

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