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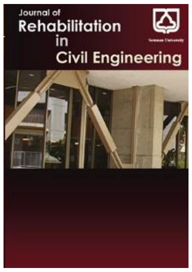

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Control of Road Settlement around Stone-Arch Bridges by Material Modification and Embankment

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ABSTRACT

Occurrence of road settlement around bridges is considered as one of the common problems of road operations. In buried bridges, especially in deep valleys, where it is not possible to use soil compaction machinery, significant settlement is observed after road operation. Such settlement mainly reduces the ride quality as well as the safety of the crossing. Based on experience, the deeper the valley and the weaker the soil, the greater the settlement created in these embankments. In this paper, in addition to field assessment of settlement in buried bridges, a suitable method has been presented for embankment around these bridges. In this regard, by finite element method, a sample of bridges buried in deep valleys has been modeled in which the settlement was calculated. The results of the finite element method were compared with the field values of the settlement at one of the studied bridges. The results showed that the settlement was directly related to the width and depth of the valley, the volume of the embankment and the soil type. Also, the results of numerical studies by finite element method showed that the created settlement was strongly affected by the modulus of elasticity of the soil compared to other parameters. If the modulus of elasticity of the materials reduces, the settlement will increase significantly. In this study, a suitable method for embankment around buried bridges in deep valleys has been presented. The results of using this method showed a significant reduction in settlement around buried bridges.

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1. Introduction

One of the important issues in achieving an efficient and appropriate road system is to pay attention to the technical buildings of the road, especially the construction and maintenance of bridges, which will include several factors. One of these parameters is how to build the embankment behind the abutment located in deep valleys and its proper compaction. Since in this type of valleys, the traffic of road construction machinery for embankment compaction is not easily possible, usually the compaction is not done properly and after a short time of road construction, the embankment subsides and there will be significant up and down before entering the bridge, causing an impact to the car, affecting the shelf life of the road and the quality of the pavement, and reducing the quality of the ride. The creation of such settlement also causes water infiltration, cracks in the pavement and embankment permeability. By performing a set of tasks, embankment settlement can be controlled, which results in providing safety and increasing its efficiency. Therefore, it is important to study in this field.

Most studies in this field are about the properties of the soils used, the method and level of soil compaction, the level of critical load and its location, as well as the prediction and control of settlement. Drosopoulos et al. calculated the ultimate failure load of the arch bridges and used the finite element method to simulate the cracking potential of the arch bridges. The researchers used a parametric method to investigate the effect of the geometric properties of the bridge on its mechanical behavior. This study showed that reducing of the rise of the arch of the bridge has generally increased the limited loads in deep and even flat arches. They found that deep arches were destroyed by the mechanism of node collapse, while compressive collapse is prevailing in flat arches. One of the most important studies on stone arches in bridges has been conducted by Heyman. According to various studies, he defined a mechanism for knot collapse in arch bridges made of building materials, which was used as a tool to determine the limiting load in these structures [1]. Orduna and Lourenco proposed two- and three-dimensional models for structures such as rock arches, which also included torsional collapse in calculations [2]. White and Hoevelkamp in a study investigated the settlement in culverts caused by foundations located on dense coarse-grained soil [3]. Xiaoxi Liu et al. in a numerical study predicted the settlement of culverts under high embankment and showed that settlement was affected by the soil below the culverts [4]. Sargand et al. proposed methods for predicting the settlement of surface foundations at the base of bridges located on coarse-grained soils without adhesion using cone penetration test (CPT) [5]. Jenkins and Lawson, using the finite element method, investigated the settlement of prefabricated culverts under high embankment and studied the effect of construction stages on their settlement rate [6]. Marfavi et al. showed that the cause of scouring in the bed of collapsed pier was the high shear strains of the bed, bed shear strength parameters reduction and as a result, reducing the bed resistance to the scouring [7]. Therefore, few studies have been conducted on the settlement of arch bridges and comprehensive studies are needed in this regard. There are also studies that concentrated on the applications of soft computing and reliability based approaches in geotechnical and civil engineering context [8–10].

In this study, first, we have provided basic and general data about the condition of roads and bridges in the study area (Ilam Province) in terms of the length of the bridge opening, the material used in the bridge body, the height of the soil to reach project line, etc. For the field investigation of the settlement, one of the existing bridges (located in a deep valley) in which the height of the embankment to reach the project line is significant (about 30 m) has been studied. First, we collected data on how to build this type of bridge, compaction and type of soil around it. Then, the bridge and the surrounding soil were modeled and analyzed based on the data obtained from the field observation by finite element method and critical displacement and stress have been investigated in both traditional embankment and the proposed methods.

2. Field study

2.1. Site description

For the field and real investigation of the settlement around this type of bridges, a stone arch bridge with an embankment height of about 30 m and high settlement has been selected as the studied bridge. Figures 1 and 2 show the general view of this bridge, the height of the embankment and the settlement created. Table 1 presents the general specifications of the bridge. This bridge is located 14 km away from Mehran.

Table 1. Characteristics of the studied bridge.

Type of bridge	Span length (m)	Height of bridge (m)	Height of embankment (m)
Stoned arch	4	3.2	30

Fig 1. Overview of the bridge.

Fig 2. Settlement created at the location of the bridge.

According to geological studies, the soil of the bridge valley walls is a combination of limestone and alluvial soil. In the lower part of the bridge, to prevent soil movement and embankment stability, the gabion has been used as a cover for part of the embankment.

In order to measure the settlement created on the studied bridge, several points were determined on the road surface and along the bridge and the coordinates of the given points (Figure 3) were measured twice and at an interval of 180 days using a surveying camera. Finally, the longitudinal profile of the path was drawn (Figure 4). The embankment settlement in the first measurement and in the maximum amount was 52 cm in relation to the entrance of the bridge from the west (point No. 3 in Figures 3 and 4), and 61 cm in the second measurement. This settlement is sum of immediate settlement and consolidation settlement. Immediate settlement on the ground immediately after loading will occur, due to elastic deformation of the soil.

A large part of the settlement can be explained as follows: the volume of the embankment in this bridge is high and there is no factor against the lateral movement of the embankment. Another part of the settlement can be attributed to creep in the soil.

The presence of the settlement has caused the asphalt surface to tension at the entrance and exit of the bridge and cracks to form across the road (Figures 5 and 6). As shown in these Figs., over time a significant difference was in the cracks created along the road.

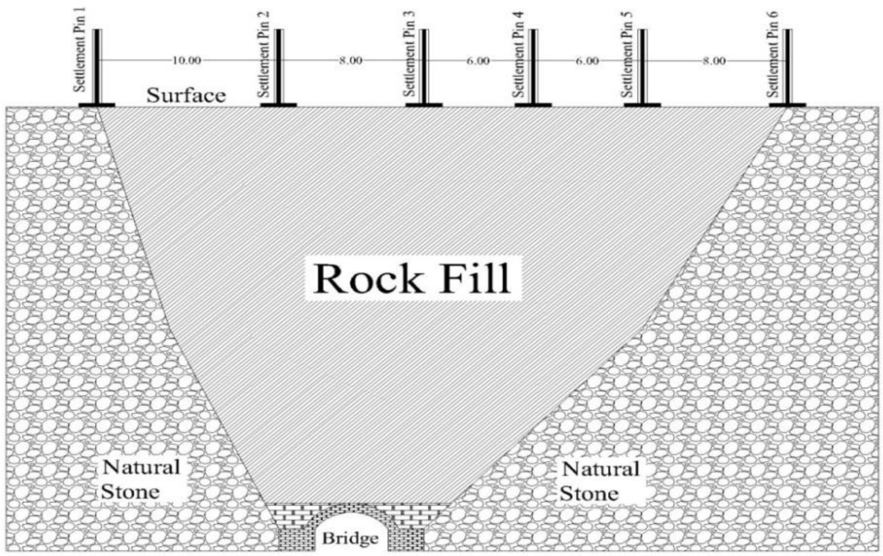

Fig 3. Designated points on the bridge deck to measure settlement.

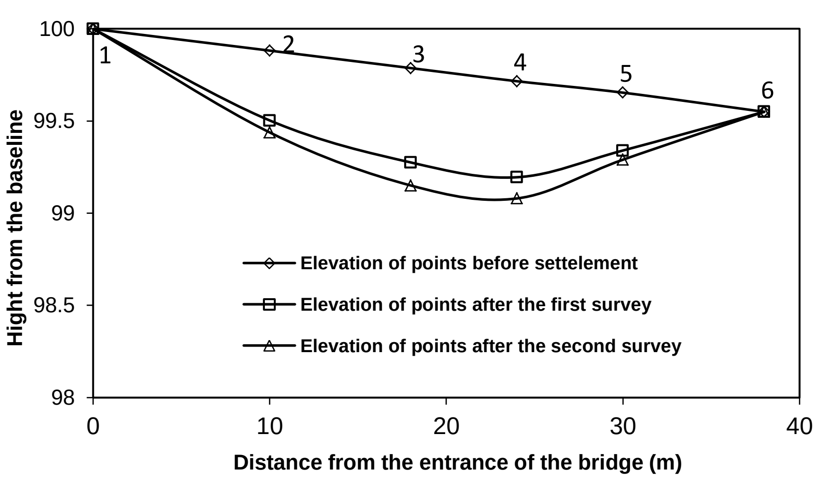

Fig 4. Longitudinal profile of the path at the bridge site during different monitoring periods.

Fig 5. Condition of the cracks in the first observation (2019-12-11)

Fig 6. Condition of the cracks in the second observation (2020-06-06)

One of the major known damage to roads is the occurrence of settlement around bridges and at the embankment of abutment, as a result of which the asphalt surface suffers from cracks called Up Down Cracking. Asphalt surface is subjected to tensile stresses due to embankment settlement and cracks are formed in the pavement surface. This failure is often reflected in the form of a concave arch on the asphalt surface. This failure is caused by the lack of proper compaction of embankment layers around the bridge abutment. Improper compaction of the embankment is caused by various reasons such as improper execution and the great depth of the embankment where it is not possible for rollers or similar machines to move on the layers and/or the narrow width of the bridge. Therefore, under such conditions, the embankment is not compacted to the required level and finally the settlement phenomenon will occur after the traffic crosses the bridge.

3. Prediction of the settlement using settlement-time curves obtained from mathematical models

One of the important methods for predicting post-construction embankment settlement is to use the curve fitting method based on the observational data of the settlement. These curves show the settlement as a function of time. These curves include Exponential, Hyperbolic, Poisson, and modified Weibull curves. Table 2 summarizes the equations of these models.

Table 2. Mathematical equations of models presenting the settlement-time curve.

Model	Formula
Exponential	$S=a.e^{bt}+c$
Hyperbolic	$S=a+b/(t+c)$
Poisson	$S=a/(1+b.e^{-ct})$
Modified Weibull	$S = a.e^{b(t+0.001)^c} + d$

Where t is the elapsed time, S is the predicted settlement, a, b, c and d are constant coefficients. In these models, the final settlement can be estimated at t=∞. Figure 7 shows the settlement-time curve obtained from these models. These curves can be used to view data of the settlement. These Figs. simply show that the end of each settlement curve is horizontal, indicating that the settlement in the upper layers of the embankment has reached a steady state.

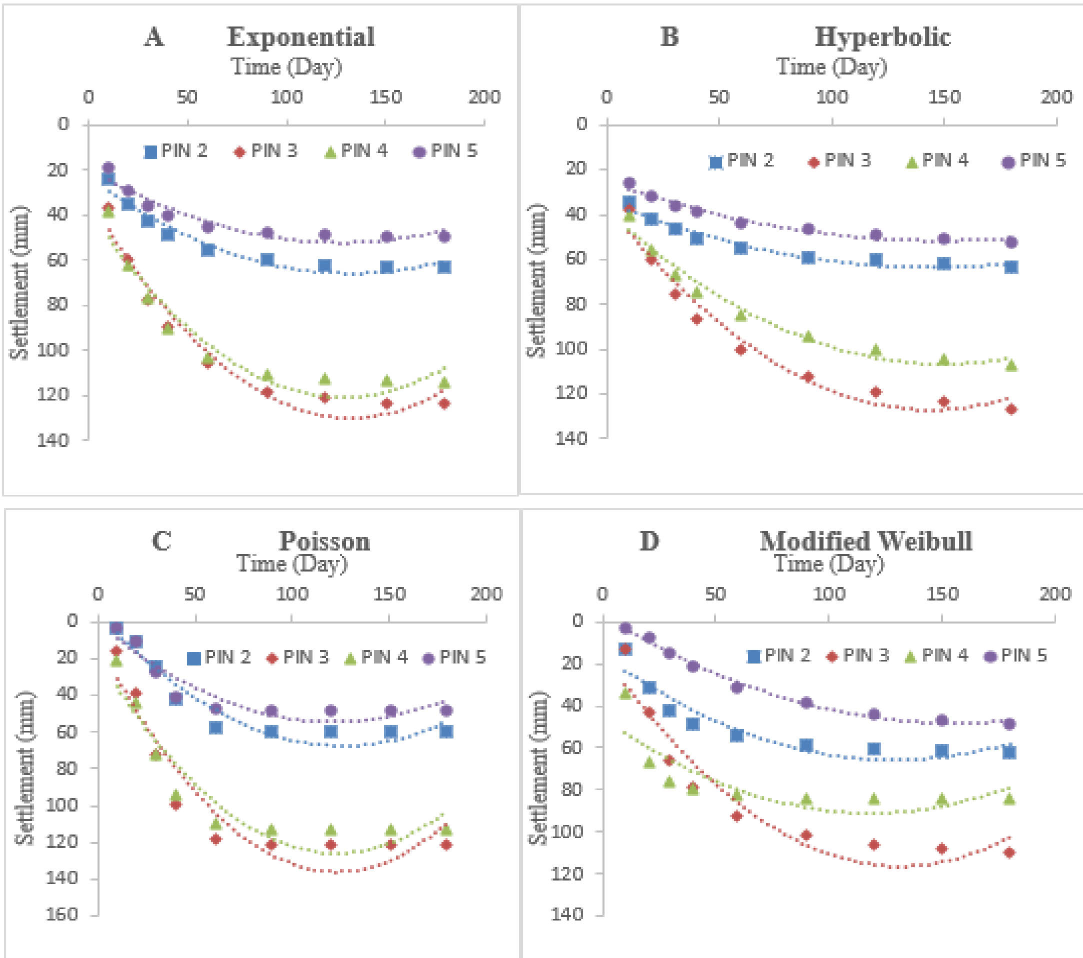

Fig 7. Settlement-time curve obtained from the models presented in Table 3.

In Figure 3, six points are considered for measuring the settlement, with the beginning and end points located outside the embankment having almost no settlement. Therefore, Figure 7 shows the settlement-time curve for points 2, 3, 4 and 5. At points 3 and 4, which are located at a distance of 10 and 18 m from the western entrance of the bridge, given that the height of the embankment is the highest, the settlement of these points was maximum, which results from the output of used models and in-situ measurements also illustrate this point.

The settlement-time curves presented in Figure 7 show that the in-situ regression analysis is in good agreement with the predictions obtained from the interpolation of the models, indicating that these models can be used to predict embankment settlement before construction.

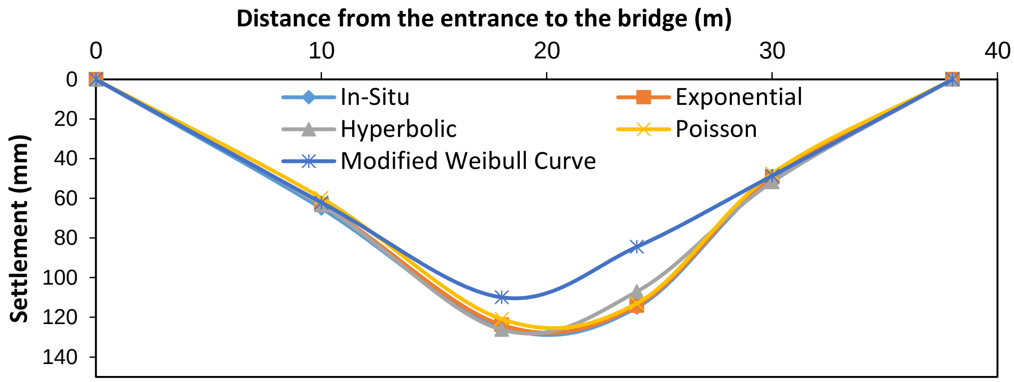

Fig 8. Comparison of the results obtained from mathematical models and field observations.

Figure 8 compares the results obtained from mathematical models with field observations. As shown in this Fig., there is good agreement between the results obtained from these curves and the field observations. Among these curves, the exponential curve is more accurate than the other curves.

4. Finite element modeling

4.1 .Finite element model

Stone-arch bridges may be complex in terms of boundary conditions, geometric dimensions and material characteristics. Therefore, numerical simulation can be used to analyze soil pressure and deformation of these bridges. In this paper, to simulate the embankment consolidation process in the layers, the finite element method has been used by Plaxis software, a two-dimensional model 15-node elements were used to mesh the model and the effect of mesh size has been checked in each analysis. In this model, the mesh compaction is reduced by moving away from the bridge body and moving towards the embankment. In Plaxis, the average element size (AES) is calculated based on the external geometric dimensions (X_{max}, X_{min}, Y_{max}, Y_{min}) and the number of triangular elements created (nc):

$$AES = \left[{}^{(X_{max} - X_{min})(Y_{max} - Y_{min})}/_{n_c} \right]^{0.5} \quad (1)$$

Plaxis provides a set of behavioral models to the user, the most suitable for analyzing the model in this study is the elastic-plastic model with hardening behavior. The following is a brief description of the behavioral models of Mohr–Coulomb and hardening soil.

Mohr–Coulomb

This behavioral model, which is the most common behavioral model used for finite element analysis, is defined with 5 parameters Young's modulus E, Poisson's ratio ν, friction angle φ, cohesion C and dilatancy angle ψ, and the stress-strain relationship is considered as fully elastoplastic (Figure 9).

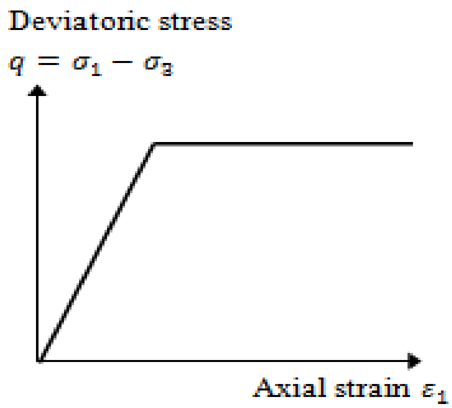

Fig 9. Result of a standard triaxial drainage test to determine soil hardness parameters in Mohr–Coulomb model.

When using Plaxis code to model coarse-grained soils, soil adhesion can be considered zero, but many parameters are not well defined and some options may not work well. In Plaxis manual, it is recommended to consider a minimum amount for soil cohesion.

Hardening soil model

This behavioral model, developed by Schanz et al. is considered as a hyperbolic stress-strain curve [11]. (Figure 10)

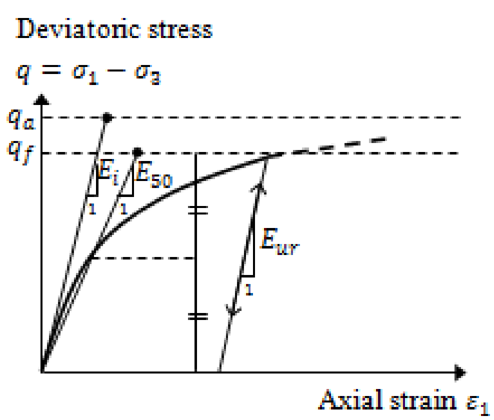

Fig 10. Result of a standard triaxial drainage test to determine soil hardness parameters in the hardening soil model.

In fact, this model eliminates the major disadvantages of Mohr–Coulomb model by adding a cap surface to model the plastic flow under uniform stresses, as well as the expression of the plastic flow before failure by applying the matched hardening law. In this model, the hardening parameter is controlled by the deflection strain controlling the deflection yield level and the plastic volumetric strain controlling the cap area. Also, we considered the hardening and elastic modulus as limiting stress functions. The advantage of this behavioral model over other models is that just as in reality soil hardness depends on comprehensive stress, in this model the hardness parameter is determined by a reference cyclic stress. In this model, the collapse criterion is similar to Mohr–Coulomb model and in it the soil hardness is defined according to the loading, triaxial loading, oedometer loading (consolidation) and loading- unloading conditions, according to the following equations:

$$E_{50} = E_{50}^{ref}\left(\frac{c\ \cos\varphi - \sigma_3^{'}\sin\varphi}{c\ \cos\varphi + P^{ref}\sin\varphi}\right)^m \quad (2)$$

$$E_{oed} = E_{oed}^{ref}\left(\frac{c\ \cos\varphi - \sigma_3^{'}\sin\varphi}{c\ \cos\varphi + P^{ref}\sin\varphi}\right)^m \quad (3)$$

$$E_{ur} = E_{ur}^{ref}\left(\frac{c\ \cos\varphi - \sigma_3^{'}\sin\varphi}{c\ \cos\varphi + P^{ref}\sin\varphi}\right)^m \quad (4)$$

Where E_{50}^{ref}, E_{oed}^{ref} and E_{ur}^{ref} indicate the hardness at the reference pressure P^{ref} (by default $P^{ref} = 100\ {}^{kN}/_{m^2}$). $\sigma_3^{'}$ is effective limiting pressure in the triaxial test is considered to be in the compressive state with a negative sign. m is the parameter expressing the degree of dependence of soil hardness on the level of enclosing stress.

The Young's modulus defined in Mohr–Coulomb model is usually equal to E_{50}^{ref} defined in the hardening soil model. For other hardness parameters we also have: $E_{ur}^{ref} = 3E_{50}^{ref}$ and $E_{50}^{ref} = 1.25E_{oed}^{ref}$.

4.2. Details of finite element model

Due to the focus of studies on settlement assessment of the existing bridge on one of the main roads, finite element modeling has also been performed on the same bridge. Plaxis software can perform analysis in plane strain, axisymmetric and simplified three-dimensional states. In this study, the analysis was performed in plane strain state. Figures 11 and 12 show the finite element model and how to apply the load as well as its mesh.

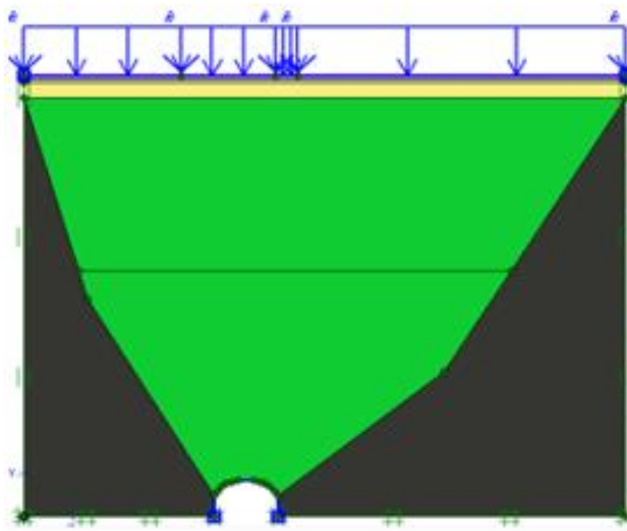

Fig 11. Modeling geometry and applying overhead.

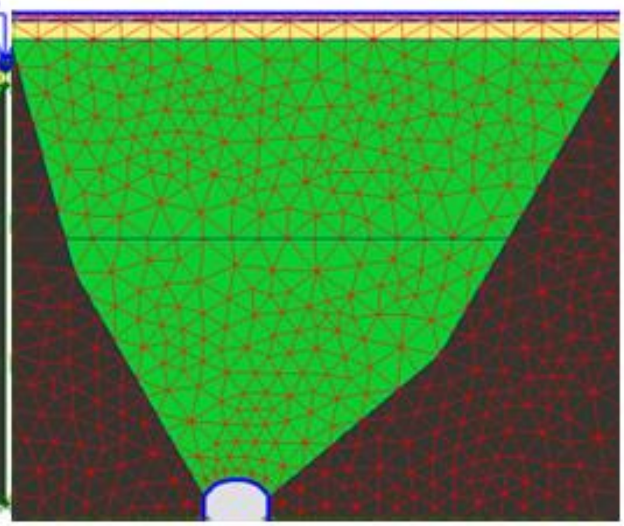

Fig 12. Model mesh.

4.3. Determining the specifications of materials

4.3.1. Pavement materials

In numerical analysis, pavement layers have been also modeled. The specifications of the materials used in the model are listed in Table 3. In modeling the surface layer (asphalt layer), the plate element and the specifications of asphalt materials had been used (Table 4).

The materials used in the upper layer of the embankment (which is the last layer of the embankment with a thickness of 1.05 m) have also been extracted from the reference [12]. These specifications are presented in Table 3.

4.3.2. Embankment materials

Since at the time of conducting this study, the exact specifications of the materials used in different parts, including the embankment and the bridge body, were not available, the parameters related to these parts were obtained from performing retro analysis by finite element method. For this purpose, in this method, more observational data such as settlement, soil pressure, etc. have been used.

The specifications of these materials are given in Table 3.

4.3.3. Bridge

The studied bridge was of the arch-stone or buried underground type, which was modeled using Plate element and common specifications for stone buildings, which are presented in Table 4.

4.3.4. Valley trenches

The material of the valley trenches is limestone and alluvial, the specifications of these materials are also extracted from reference [12] and listed in Table 3.

Table 3. Specifications of materials used in nonlinear finite element analysis.

Type	E_{50}^{ref} (kN/m^2)	E_{oed}^{ref} (kN/m^2)	E_{ur}^{ref} (kN/m^2)	m	C (kN/m^2)	Φ (degree)	ψ (degree)	γ (kN/m^3)	ν
Base	2.5e5	2.5e5	2.5e5	0.5 5	5	40	10	17.5	0.3
Sub-base	2e5	2e5	6e5		10	25	0	16.5	0.3
Compact Layer	2.3e5	2.3e5	6.9e5		1	36	12	16	0.2
Rock fill	1.12e4	1.12e4	3.36e4		0.9	30	0	20.3	0.29
Stone	5.6e7	5.6e7	1.68e8		1	45	15	25	0.3
Natural Stone	6.37e7	6.37e7	1.91e8		0.5	45	15	25	0.3

Table 4. Specifications of asphalt surface and bridge construction materials.

Type	EA (kN/m)	EI (kNm^2/m)	t (m)	ν
Pavement	1.92e6	2304	0.12	0.35
Abutment	4.464e8	1.49e8	2	
Arch	1.339e8	4.018e6	0.6	

Where EA is the axial hardness, EI is the flexural hardness, t is the layer thickness and ν is the Poisson's ratio.

4.4. Model analysis

After making the model, defining the specifications of materials, boundary conditions, meshing and loading (combination of 40 tons truck load and equivalent linear load) the model has been analyzed. Figures 13 and 14 show the general displacement and the settlement. In order to locate the maximum settlement, the critical load caused by the 40 tons truck was applied to different points and the model was analyzed. By doing this process, the critical location of the load was obtained at a point 1.7 m to the left axial of the bridge, which corresponds to the location of the rear axial of the truck.

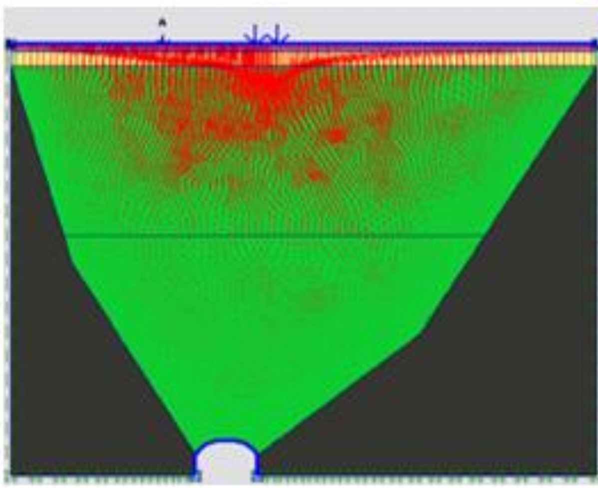

Fig 13. Total displacement of the embankment.

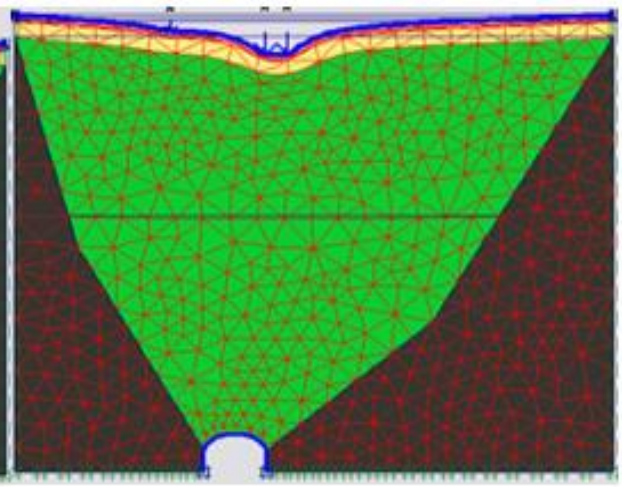

Fig 14. Modified geometry of the model.

The focus of the displacement contours indicates the displacement at the loading points. At the points where the critical load is applied, these values are larger, indicating more deformation at these points than at other points.

The settlement obtained from the analysis is 49 cm and very close to the 52 cm settlement that actually took place at the site. This consistency can be attributed to the use of a suitable soil behavioral model for numerical analysis and the dependence of the main soil parameters on comprehensive stress. Figure 15 shows the actual settlement and the settlement obtained from finite element analysis.

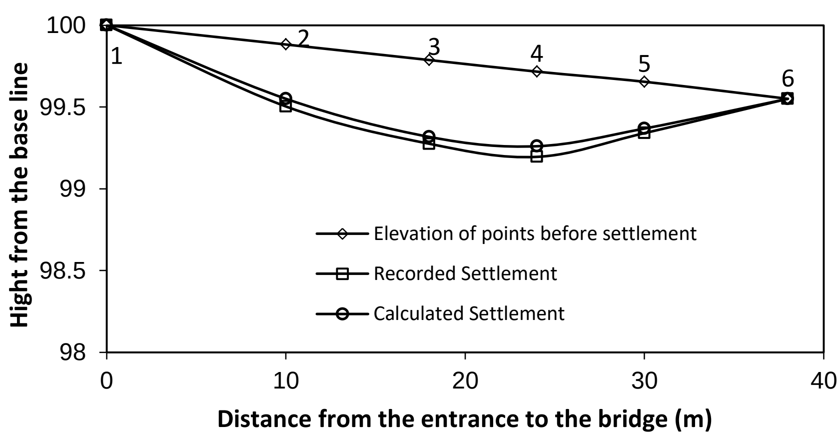

Fig 15. Comparison of field settlement and settlement obtained from the software.

The settlement can be attributed to the presence of unsuitable soil in different layers, improper embankment, lack of proper exploitation, lack of factor against lateral movement of the embankment, improper compaction and the behavioral nature of the soil. One of the ways to control the settlement, in addition to the proper embankment, is to use materials that have less compaction. For this purpose, the resistance parameters (elastic modulus, internal friction angle and adhesion) of the soil used in the bridge embankment have been changed and the model has been analyzed. This process has continued to the point that using a combination of rock and filler materials (similar to fine sand) which also have a high elastic modulus, the least settlement was made in the bridge embankment. The use of these materials, which are available in most areas and do not require much compaction, is feasible in practice and will be widely used on bridges where there is a limitation of dimensions for the movement of compaction machinery. In addition to controlling the settlement, they can be used as drainage and control of pore water pressure. With the above combination of the finite element method, in a field study, this method has been used in a sample of bridge construction on the main road of Darreshahr and Abdanan, Ilam Province. The settlement in the embankment of this bridge is approximately 3.5 cm. Figure 16 shows the method of execution of materials. Figure 17 shows the result of using the combination of these materials, causing a significant reduction in the embankment of the bridge.

Fig. 16. A combined embankment.

Fig. 17. Example of a bridge by an innovative method.

As mentioned earlier, the specifications of the materials used for the analysis had a direct effect on the settlement. Among these characteristics, the elastic modulus is more effective than other parameters and a change in it causes a significant change in the created

session. The analysis performed in this study showed that a reduction by 10% in the elastic modulus of materials has increased the settlement by 4 times. Therefore, it can be said that one of the methods to deal with settlement in high embankments is to control the elastic modulus of used materials.

4.5. Finite element modeling of the innovative method of embankment

In order to perform this method, it is suggested to fill row-by-row from the bottom of the valley to the top of the arch and / or the height by dry-stone walling to which the compaction machinery had access (using stone materials and fine sand) and then with the materials suitable for embankment, the rest of the valley and the main layers of pavement were executed. Based on the scientific and practical experiences of the co-authors of this article, using this method is feasible without the need for the least road construction machinery, which is very useful and economical.

If machinery traffic is not possible from the arch of the bridge to a certain height, the depth of the valley should be filled until it reaches that level by dry-stone walling (using stone and fine sand). In addition, by road construction machinery, the usual embankment operations can be continued. This process should be repeated and completed to the height at which the machinery can travel.
Modeling and analysis of this method have been done in two cases. In the first case, the space in the valley up to the top of the bridge arch is filled with a combination of stone and fine sand. For this purpose, the existing space is divided into 30 cm rows and the specifications of coarse-grained materials are defined. For the space between these rows, the specifications of sand have been used. In the second case, assuming that the machinery do not have access to the upper level of the bridge arch, these materials are used up to the accessible level of the machinery (Figures 18 and 19). The parameters defined in this part, which are derived from references [12] and [13], are presented in Table 5. The other parameters are the same as the parameters in Tables 3 and 4.

Table 5. Specifications of materials used for finite element analysis of the innovative method.

Type	E_{50}^{ref} (kN/m^2)	E_{oed}^{ref} (kN/m^2)	E_{ur}^{ref} (kN/m^2)	m	C (kN/m^2)	Φ (degree)	ψ (degree)	γ (kN/m^3)	ν
Rock fill	2.1e5	2.1e5	6.3e5	0.55	0.1	42	12	15.5	0.3
Limestone	5.6e7	5.6e7	1.68e8	0.55	0.5	45	15	25	0.3
Sand Fill	4.5e4	4.5e4	2.8e5	0.5	2	35	5	17	0.2

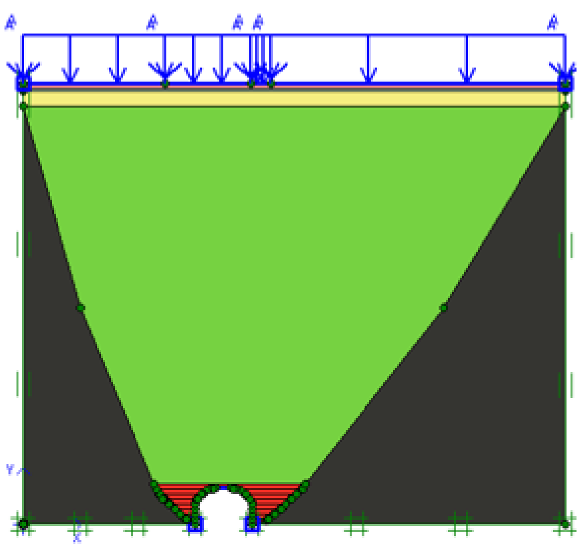

Fig. 18. Geometric shape of the model using the innovative method (dry-stone walling up to the bridge arch).

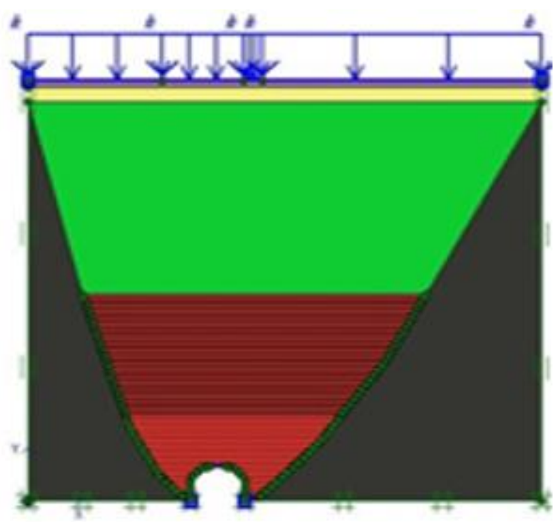

Fig. 19. Geometric shape of the model in the case of using the innovative method (dry-stone walling up to the machinery access).

As mentioned earlier, the results of numerical analysis using this method showed a significant reduction in road surface settlement, which in the first case (Figure 18) is equal to 5.1 mm, and 4.7 mm in the second case (Figure 19). Figure 20 shows settlement in different cases. As shown in this Fig., settlement obtained from the innovative method has the lowest value compared to other cases.

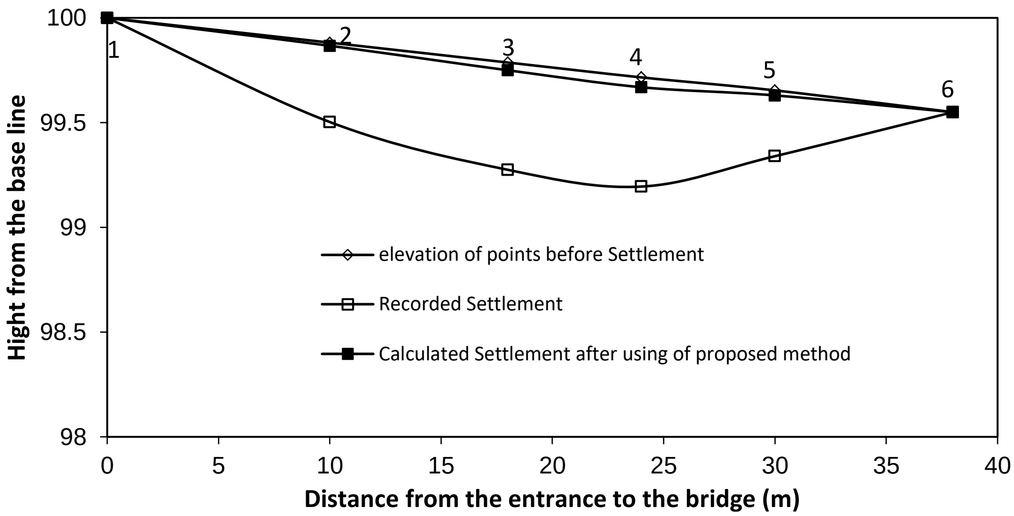

Fig. 20. Comparison of site-recorded settlement and settlement after the use of aggregates in the bridge embankment.

Theoretically, the use of coarse-grained materials with high elastic modulus reduces the settlement and in case of settlement, the settlement of these materials is instantaneous and can be eliminated at the very beginning of operation. Therefore, it can be said that the use of this type of material is a suitable method for embankment in deep valleys.

5. Conclusion

According to the studies conducted in this field, the following results have been obtained:

- For predicting the settlement in the embankments, four curve models have been used, which the exponential curve was more suitable than other curves.

- The results obtained from the calculation of settlement above the embankment by finite element method were consistent with the observational data and settlement above the embankment was nonlinear.

- One of the most important parameters affecting settlement was the elastic modulus of materials used. In such a way that a reduction by 10% in the elastic modulus increased the resulting settlement 4 times.

- Field studies on buried bridges showed that settlement was directly related to the height of the embankment and the main settlement was between the axis of the bridge and the beginning of the embankment.

- Free fall is not suitable for pouring embankment materials behind bridge walls and not effective on achieving the required compaction.

- Depending on the dimensions required for using compaction machinery in compacting embankment layers, up to the desired height, the proposed embankment method can be used, which will cause less settlement.

- The results of numerical studies showed that using coarse-grained materials in combination with filler materials similar to sand will reduce settlement by about 85% compared to the traditional embankment method.

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