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Comparative Study of a Subgrade Coefficient Reaction on an Arched Dam Using the Winkler Foundation Model

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ABSTRACT

Foundations are one of the most important parts of different structures. The interaction between a foundation and the soil is an important factor to evaluate the behavior of the structure. The behavior of the subgrade is complicated and disordered against the forces. So, instead of modeling the soil media with its original nature, the subgrade in the subject of interaction of structure-soil will be replaced with a much simpler system which is called subgrade model, and one of the most known and oldest one of them is Winkler model. The body of the dam is modeled with a concrete wall by using the Solid187 element and the subgrade in the first mode as a flexible weightless foundation. In the second model, the COMBIN14 element with the subgrade reaction coefficient equal to 10×10^6 for central springs and 12×10^6 for lateral springs is considered. The obtained results are presented in different diagrams.

1. Introduction

Analysis of foundations is so important in civil engineering, because, first, in case of foundation damage, the whole system of structure will be questioned and repairing operation is not cost-efficient, since a large part of the structure is damaged, and second, we don't usually have enough

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information about condition of soil in the site and the soil and foundations which are beneath the structure, do not have a fixed behavior. So understanding the analysis methods of foundations is so important for designing and analyzing of foundations in a correct method [1].

Analysis of foundations usually takes place with two methods "flexible" and "rigid". About single foundations, the assumption that foundations are rigid is so close to reality, considering their common sizes. But about the band and wide foundations, the assumption of the full rigidness of the foundations is not completely correct and in many cases, it leads to wrong designs. The rigidness solution for analysis of foundations with classic methods is based on static balance. In this method, it is assumed that the foundations are much more rigid and harder than subgrade, which means that any kind of changes in the foundation is so small that they have no important effect on the distribution of pressure to the ground. So the largeness and distribution of foundation bottom pressure only depend on the weight of the foundation and the load, and in case of applying the outcome of these loads on foundation surface center, the reaction would be invariable and in case of a different situation, it would be variable and linear. With this assumption and the linear distribution of pressure beneath the foundation, calculation of bending moments and form changes will be easy for single and wide foundations. Although this kind of analysis is suitable for single foundations, it's not possible to model wide and band foundations with this method, because the ratio of width to thickness is so high in wide foundations and the assumption of rigidness is not even close to reality. In non-rigid methods form changing effects in foundations will be considered. So there is a need for a relation between tension and displacement, which is covered by subgrade reaction [1].

Sometimes applying the effects caused by the surrounding environment in the analysis process makes structure response and its vibrational behavior changes a lot. In this situation, the structure must be analyzed considering the existing interactions between the structure and its surrounding environment. In this method, the effects of each environment will be applied by using forces which depend on geometric and mechanical characteristics of the environment, on other environments. These forces usually have a relation with mutual displacements of adjacent surroundings and the basic part of this relation is a matrix which is called impedance matrix, and it is obtained for a foundation of a stone range which is around the arched dam. This matrix subordinates on frequency and depends on geometric and mechanical characteristics of dam valley. The foundation of the stone range affects the behavior of the adjacent structures by three important characteristics which are rigidness, weight, and damping. Only two characteristics of weight and damping are applied in dynamic analysis and allow waves to propagate in the aforementioned range [1].

Gerolymos and Gazetas (2006) [2] studied Winkler model for lateral response of rigid caisson foundations in linear soil. Karapiperis and Gerolymos (2014) [3] studied finite element versus Winkler modeling for combined loading of caisson foundations in cohesive soil. Prendergast and Gavin (2016) [4] conducted a comparison of initial stiffness formulations for small-strain soil–pile dynamic Winkler modeling. Asakereh and Mossafa (2017) [5] investigated the subgrade reaction coefficient in sandy soils of Bandar Abbas city. The results of their study showed that an increasing footing diameter which leads to the decrease of the K_S. This fact is because of an increasing load area which concluded to the increasing of the settlement. It is found that increasing each of the strength parameters of the soil (c,∅) can be expected an effect on increasing the subgrade reaction. Lopez et al (2017) [6] used Numerical methods for SSI analysis of offshore wind turbine foundations. They have presented a standard method based on a beam on nonlinear Winkler spring. Akmadzic et al (2018) [7] evaluated Influence of the subgrade reaction coefficient modeling on the simple 3D frame.

2. Winkler model

The behavior of subgrade soil is completely complex and irregular against the applied loads, so instead of modeling the soil media beneath infrastructure as its original nature, the subgrade will be replaced with a much simpler system which is called the subgrade, and it is one the oldest and most known models herein are Winkler model [1].

Winkler (1867) assumed the soil -media to be consists of similar linear elasticity springs which are independent of their two sides and are separately close to each other, and in each point, the relation between tactile pressure (P) with subsidence (s), is established with the subgrade reaction coefficient as following [1]:

$$P = K_s S \quad (1)$$

Where P is the applied pressure, S is the displacement of foundation and K_s s is the subgrade reaction coefficient. In fact, in this method, the infra-foundation will be replaced with hypothetical springs and the spring contact is K_s [1].

In most of the cases about interaction of structure and soil, lots of researchers such as Zimran (1888), Hetni (1946), Popvu (1951), Terzaghi (1955,1932) (2), Vesic (1961) [8], Herwats (1989,1983) [9], Daloglu and Vallabhan (2000) [10] used Winkler model. This is the most common model of subgrade which is used among lots of designers and has been used since the late 19 century and lots of computer software has been developed based on this content. But the basic problem for using this method is determining the numeral value of the subgrade reaction coefficient or the rigidness of elasticity springs.

2.1. Effective factors on subgrade reaction coefficient

Subgrade reaction coefficient is the most important parameter of the Winkler model and it has the dimension of force on cubed length. The physical behavior and mechanical characteristics of subgrade soil can be modeled only using these springs [2]. Terzaghi (1955), in his comprehensive article, studied the influence of effective factors on K_s separately in horizontal flexible bars and wide foundations, and he also used the articles of other researchers. He indicated that K_s is not a characteristic of soil and besides its dependence to the nature of subgrade and stratification [11] it is depended on geometric features of load transferring system [2] and even the type of applied load and the distance of loads from each other [12]. In general, the different methods of determining subgrade reaction coefficient can be classified as follows.

1. Experimental methods

2. Relations which are represented empirically by researchers by using elasticity theory

In this relation the obtained elasticity theory has been used:

$$K_s = \frac{E_S}{B(1-\vartheta_S^2)MI_FI_S} \quad (2)$$

Where E_S and ϑ_S^2 are the elasticity coefficient and Poisson ratio of soil respectively; B is the minimum lateral dimension, I_F *and* I_S are affected coefficients which depend on the ratio of depth of infrastructure to dimensions ϑ_S, and its value can be determined by using related tables and diagrams. M is the symbol of a coefficient in which its value for corner, edge, and center of infrastructure is 1, 2 and 4, respectively [12].

2.1.1. Geometry and numerical parameters of the dam body and foundation

Fig. 1 shows the geometry of the arc dam model with 10-node three dimensional elements, quadratic structure of SOLID187. This dam has a concrete wall with a uniform thickness of 6 meters, a dam's crest of 250 meters, it is 130 meters long and the horizontal curve radius is 156 meters. This dam model is placed on a weightless flexible foundation with zero density, elasticity of 21×10^3 KN and Poisson ratio of 0.25.

Table 1
Characteristics of concrete arc dam material.

body	foundation	parameters
30	0	Dry density (KN/m^3)
21×10^6	21×10^3	Elasticity Coefficient
0.30	0.25	Poisson ratio ν

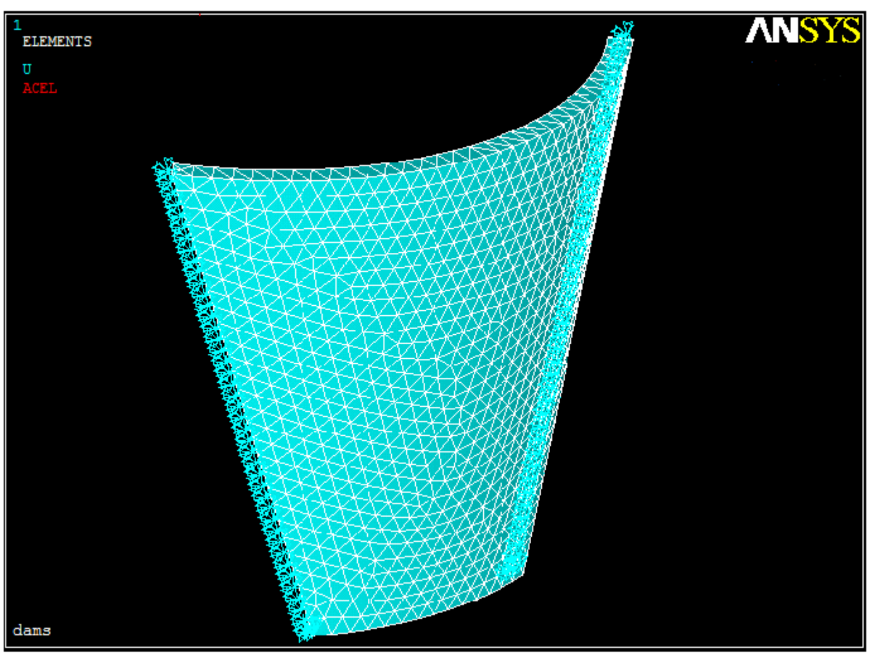

Fig. l. Geometrical model of the dam.

3. Numerical analysis

When using constraint element model in analysis, in the first step of analysis, a constant value of reaction coefficient is used through the whole dam and the interactions among springs are neglected.Usually using computer programs of limited components, foundation analysis is performed in this step.

Using pressure distribution obtained from first step and neglecting foundation hardness, soil settlement in each node is calculated. The settlement is calculated using Boussinesq distribution for elasticity environment. Using the pressure distribution obtained from the first step and soil settlement from the second step, a spring with new stiffness is calculated for the node. Spring stiffness is calculated by dividing the force by location shift in each node.

In the second step, using spring stiffness obtained from first step, the foundation is again analyzed by limited components and pressure distribution is obtained. Then using the pressure distribution from previous step and the soil settlement, a spring with new stiffness is calculated for each node. In this step, foundation hardness is practically neglected.

The above steps continue till convergence is seen in results. Time convergence will be obtained when the settlement resulted from foundation analysis matches soil settlement (without considering foundation hardness). Using this method, the coefficient of subgrade reaction for different points will be obtained the value of which is different at each point. In central parts of the foundation, the subgrade reaction coefficient is lower and its value increased in foundation edges. A flexible surface with similar bending hardness is calculated under this surface, the numerical value of which increases towards the edges of surface.

Here, with regards to simultaneous effects of horizontal and vertical subgrade reaction coefficient and also using dimensional COMBIN14 element, the model is analyzed with different subgrade reaction coefficients: 26×10^6, 5×10^6, 8×10^6, 10×10^6, 20×10^6, 12×10^6, 40×10^6. When using the subgrade reaction coefficient of 10×10^6 for central springs and 12×10^6 for lateral springs, the results are nearer to the values from subgrade soil analysis in the form of a weightless flexible foundation. Here, the subgrade reaction coefficient is obtained using a 26×10^6 experimental relation. The results of analysis with subgrade reaction coefficient of 10×10^6 for central springs and 12×10^6 for lateral springs, together with the results of the flexible weightless foundation model are shown in the figure.

The model has been analyzed under the influence of its weight and supposing a foundation with no weight. Arc dam analysis has been performed in form of elasticity analysis. 7 models with stable characteristics have been examined. in each of these models, just the subgrade reaction coefficient as the variable and one state of the dam on the flexible weightless foundation are considered.

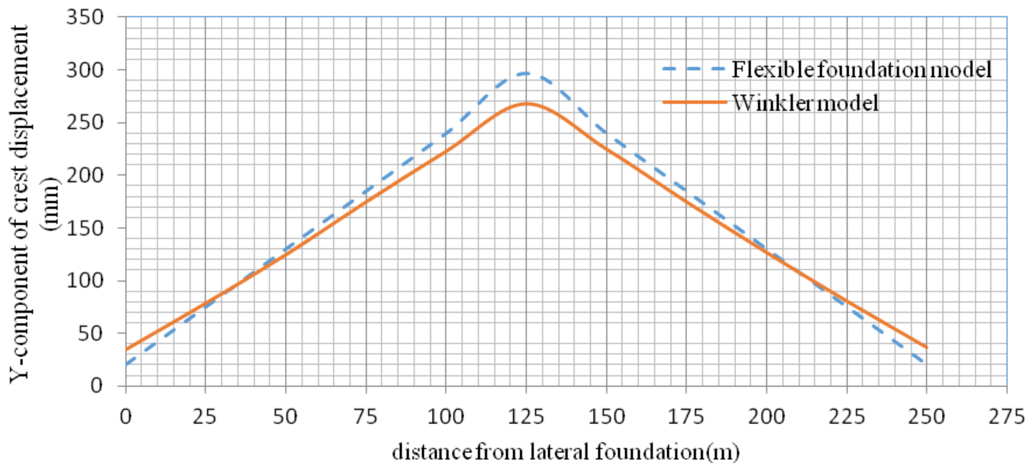

Fig. 2. The value of dam crest displacement in a perpendicular direction to dam body (y-direction) in arc dam crest (mm) against distance from lateral foundations (m).

According to fig. 2, the value of displacement in vertical direction is presented against the distance from lateral foundation. The maximum displacement in the center of dam's crest is 297mm. this displacement decreases with 0.48%gradient when getting closer to the lateral and finally reaches 20mm in the place of contact with the foundation. The results of analysis with subgrade reaction coefficient of 10×10^6 for central springs and 12×10^6 for lateral springs, together with the results of weightless flexible foundation model are shown in the figure. Moreover, the results of analyses show that inflexible foundation model, the value of perpendicular displacement of dam's crest is more than lateral foundation to the distance of 10 meters and in the center of dam's crest is lower than the value obtained from Winkler model.

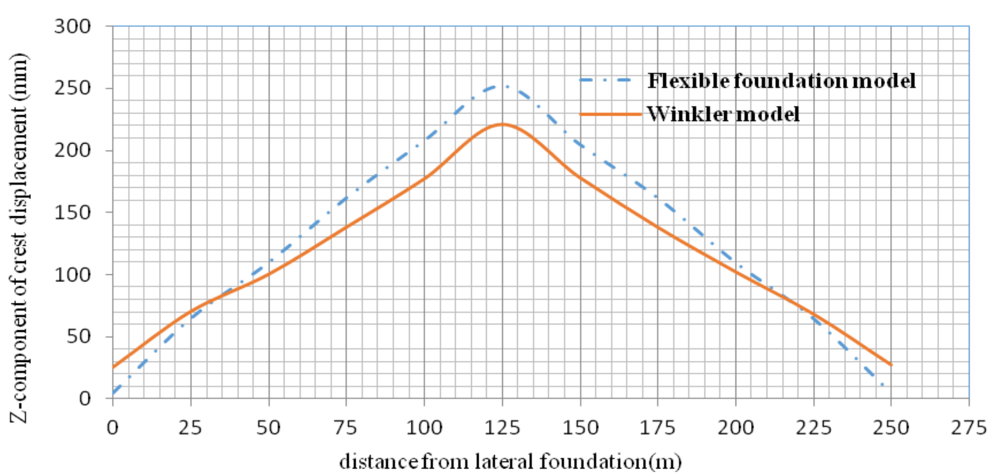

Fig. 3. The value of dam crest displacement in depth (z-direction) in arc dam crest (mm) against distance from lateral foundation (m).

According to Fig. 3, the maximum value of displacement in-depth (z-direction) in arc dam's crest is 322 mm. displacement in z-direction decreases with 0.35% gradient when getting closer to the lateral. The results of the analysis with the subgrade reaction coefficient of 10×10^6 for central springs and 12×10^6 for lateral springs, together with the results of the weightless flexible foundation model are shown in Fig. 3.

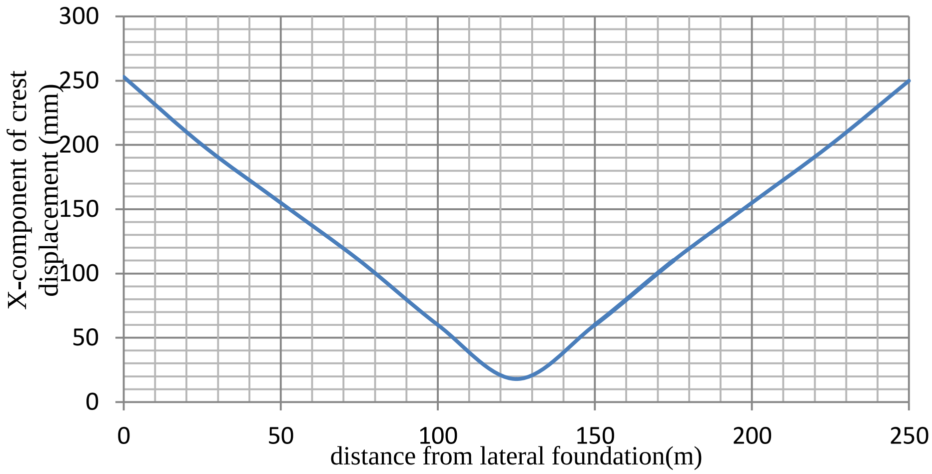

Fig. 4. The displacement of the dam's crest in the direction of the dam body (x-direction)(mm) versus the distance from the sidewall (m).

Fig. 4 shows the value of the displacement changes along the dam's crest in the x-direction (along the dam's crest length) versus the distance from the lateral succession (Winkler model). Due to the shape, the displacement value on the sides is a maximum of 250 mm, which decreases with approaching the center by 0.19% slope and reaches zero at the center of the arch dam's crest.

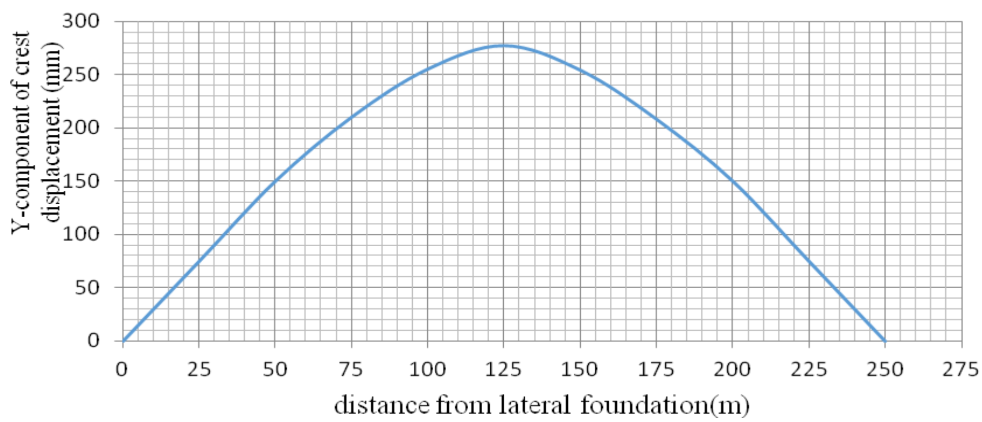

Fig. 5. Displacement value of the dam's crest perpendicular to the body of the dam (Vertical-direction) (mm) versus the distance from the lateral base (m).

Fig. 5 shows the amount of displacement in the y-direction versus the length of the dam (Winkler model). The maximum displacement in the center of the dam's crest is 277 mm. This displacement decreases with approaching the sides with a slope of 0.48%.

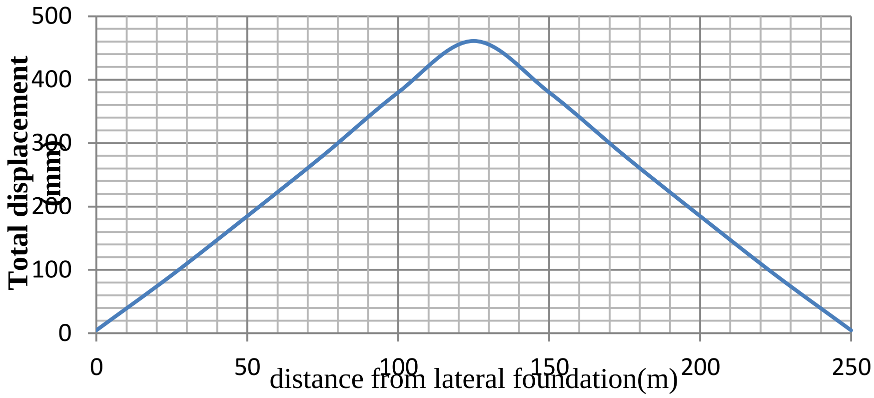

Fig. 6. Total displacement of the dam's crest (mm) versus the distance from the lateral base (m).

Fig. 6 shows the total displacement of the dam's crest along the dam's crest (Winkler model). According to the shape, the number of displacement decreases by 0.38% with the approach to the lateral slope, and at the near edge of the dam is near zero and the center of the dam's crest is maximum and equal to 461 mm.

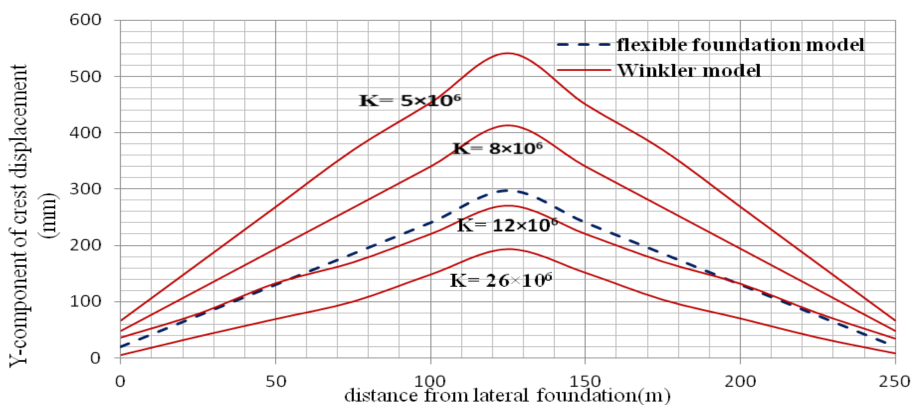

Fig. 7. The dam crest displacement for different modes of the subgrade reaction coefficient in the Winkler model.

Fig. 7 shows the displacement of the dam's crest for different modes of subgrade reaction coefficient in the Winkler modulus. The results show that by increasing the subgrade reaction coefficient, the number of displacement decreases. The results obtained when using the subgrade reaction coefficient of 10×10^6 for central springs and 12×10^6 for lateral springs are closer to the results of a flexible weightless foundation model. Because different factors such as structure geometry and number of springs affect the subgrade reaction coefficient, the optimum values obtained for similar structures cannot be used.

4. Results and discussion

- When horizontal and vertical subgrade reaction coefficients have simultaneous effects, the values of the subgrade reaction coefficient obtained from experimental equation have not acceptable results.

- The results of analyses showed that the value of vertical displacement of dam's crest inflexible foundation modeling to 10 meters distance, is more than lateral foundation and in the center of dam's crest is less than the value obtained from Winkler model.
- The use of the subgrade reaction coefficient equal to 10×10^6 for central springs and 12×10^6 for lateral springs is closer to the results of the flexible weightless foundation model.
- Acceptable results were gained by analyzing the arc dam with Winkler model using ANSYS software.
- Maximum displacement in the dam's crest is obtained from results. Displacement in Z and Y directions in the center of dam's crest is maximum.
- Due to the different factors effects on subgrade reaction coefficient, the optimum values obtained for similar structures cannot be used.

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