Deformations of reinforced-soil retaining walls

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ABSTRACT: The possibility of realistic prediction of the scope and the character of deformations of reinforced-soil retaining structures is discussed in this article. In the first part of the paper, a short review of the commonly used methods to calculate the deformations of reinforced soil (RS) structures is presented. Their advantages and disadvantages are discussed. Additionally, an original analytical method enabling assessment of strains and displacements in RS structures is described. Then, the results of using the selected available methods of describing the reinforced-soil structures deformation are discussed. Their accuracy was verified on the basis of data obtained from previously published experimental tests. Main conclusions are enclosed. Important problems which need further investigations are also identified.

Keywords: reinforced soil, walls, geosynthetics, analytical models

1 INTRODUCTION

As a result of their economic advantages and superior engineering properties the reinforced-soil (RS) structures have gained increasing popularity throughout the world. Application of the RS include retaining walls, bridge abutments, dams, embankments, industrial, coastal and military structures, and others. Typical reinforced soil structure consists of two major components: a facing element and a RS mass. A RS mass comprises closely spaced layers of material used as reinforcement and compacted granular fill soil.

Basic design guidelines for the RS structures are available. Recommendations regarding main elements such as: backfill type and level of its compaction as well as basic parameters of reinforcement layers are also enclosed (their strengths, vertical spacing, stiffness and length) - e.g. Adams et al. 2011 and Nicks et al. 2013. Although these design rules are reasonably well established, the prediction of RS structures deformations and settlements under applied service loads requires further investigation. There is no complex, commonly accepted method or procedures which can be used to solve this problem (Kazimierowicz-Frankowska 2003, Khosrojerdi et al 2017).

The problem of determining strains and displacements in the RS structures is generally complex, because several factors control the behavior of such structures. The most significant of them, identified on the basis of experimental results conducted on both laboratory and full-scale models, are: the geometry of the RS structure, the type of facing elements, the parameters of the materials used as soil backfill and reinforcement, and the level and location of acting load (Kazimierowicz-Frankowska 2003). Although individual assessment of these factors is important, their combined effects are also required to better understanding the RS structures' behavior.

From practical point of view an engineer is interested mainly in accurately predicting two types of deformations of RS structures: horizontal displacements of the facing and vertical displacements (settlements) of the crest. Although both of them are very important, the scope of this paper is limited to the problem of calculating the horizontal one. The first part of the present contribution is devoted to a short description of the commonly used methods to predict the RS structures lateral deformation. Then, the analytical method developed in IBW PAN, which can be used to solve the problem, is shortly characterized.

The last part of this paper deals with a discussion of the results obtained by using selected methods to describe the lateral deformation of the RS structure. Their accuracy was verified on the basis of data obtained from previously performed experimental tests in laboratory scale (Kazimierowicz-Frankowska 2003, Kulczykowski 2013). Main conclusions are presented.

1.1 *Methods used for calculation of the RS deformations – short characteristics and classifications*

An increasing number of studies on the problem of the RS deformations have been conducted by researchers in the last years (e.g. Khosrojerdi et al. 2017, Ozturk 2014, Wu et al. 2013, Bathurst et al. 2009, Kazimierowicz-Frankowska 2005, Kazimierowicz-Frankowska 2004, Kazimierowicz-Frankowska 2003). The review of present state-of-the art shows that a number of solusions are currently available in engineering practice. Generally, the methods of analysis of the RS structures deformations can be classified within the framework of a few groups (Figure 1). It is possible to select three main approaches to this problem. In the first of them the empirical methods are used for finding the solution (for estimating deformation of the RS structures). Empirical methods have the longest history of applications.

The first solutions (Jewell 1988, Jewell & Milligan 1989) were already developed 30ty years ago. Their authors proposed design charts which can be used to estimate lateral deformation of the RS structures. They enabled the prediction of deformations at different depths within the wall. The charts showed relationships between defined dimensionless displacement factor and the ratio of depth below the crest of construction for various backfill friction angles and dilation angles. For a long time they were very useful in engineering practice. However, their scope of applications (as for all the empirical methods) has been limited to data (and parameters) obtained from performed experimental programs.

The second and the third types of prevailing methods for calculating the maximum lateral displacements of the RS structures are based on analytical and numerical methods, respectively. They differ mathematical apparatus used for solving the problem.

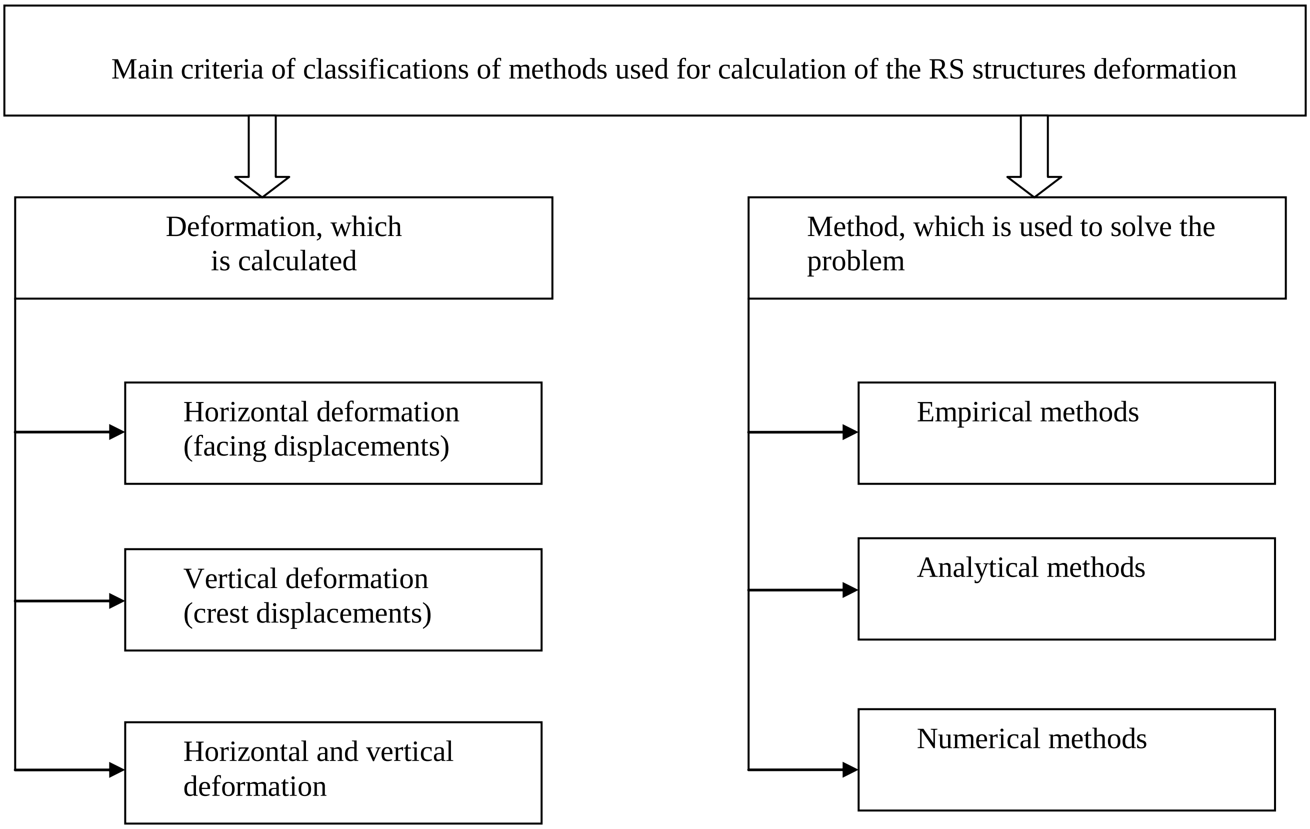


Figure 1. Methods used to calculate RS structures deformations.

The analytical approach requires high level of knowledge regarding mechanisms of working the RS structures and their particular elements (such as facing, backfill and reinforcement). The potential modelling errors performed at the initial modelling stage caused significant errors in the results of calculations.

Table 1. A short characteristic of the commonly used analytical methods

Name	References	Short description		
		Basic formulas	Notations	Assumptions
FHWA method	Christopher et al. (1990)	$\delta_R = 11.81\left(\frac{L}{H}\right)^4 - 42.25\left(\frac{L}{H}\right)^3 + 57.16\left(\frac{L}{H}\right)^2 - 35.45\left(\frac{L}{H}\right) + 9.471$ $\delta_{max} = \frac{\delta_R H}{75}$ (extensible reinforcement) $\delta_{max} = \frac{\delta_R H}{250}$ (inextensible reinforcement)	δ_R - deformation coefficient of reinforced soil wall; δ_{max} - max. lateral deformation of the RS structure L - reinforcement length; H - height of the RS wall	the value of L/H is between 0.3 and 1.175; the RS structure is placed on rigid foundations; the RS wall is reinforced with geosynthetics layers of the same size; each additional 19.15 kPa of surcharge load increases the deformation by approximate 25%
Geoservice method	Giroud (1989)	$\delta_h = \frac{\varepsilon_d L}{2}$	δ_h - deformation of the RS structure; ε_d - strain limit or max. strain in each layer of reinforcement	if the reinforcement strain is unknown it should be assumed that the strain limit is less than 10%
CTI method	Wu (1994)	$\delta_{max} = \varepsilon_d\left(\frac{H}{1.25}\right)$	H- height of the RS wall; ε_d - strain limit or max. strain in each layer of reinforcement	the strain limit is within the range between 1 and 3% for permanent walls and up to 10% for temporary walls; the height of the RS wall is less than 6.1m; the facing rigidity is low (the wrapped-face wall)
Wu method	Wu et al. (2013)	$\Delta_h = \left(\frac{1}{2}\right)\left(\frac{P_{rm}}{K_{reinf}}\right)(H - z_i)\cdot\left[\tan\left(45^0 - \frac{\psi}{2}\right) + \tan\left(90^0 - \phi_{ds}\right)\right]$	Δ_h - deformation of the RS structure; P_{rm}- max. reinforcement force at depth of z from crest; ψ - dilatation angle of soil;	$L/H \geq 0.7$; the flexible facing is assumed (the rigidity of the wall is not considered)
Adams method	Adams et al. (2002)	$D_L = \frac{2b_{q,vol} D_v}{H}$ $\varepsilon_L = \frac{D_L}{b_{q,vol}} = \frac{2D_v}{H} = 2\varepsilon_v$	D_L- lateral deformation of GRS abutments; D_V - vertical settlement of the GRS abutment; ε_L -lateral strain; ε_v - vertical strain at top of the wall	the worst-case scenario for lateral displacement is assumed (the volume change in the RS structure is zero); the soil and the reinforcement deform laterally together and have the same amount of strain

The commonly used methods for estimating the maximum lateral displacements of the RS structures are presented in Table 1. It is clearly visible that they are not very new. Most of them were established in the

90s of 20 century. Therefore, they don't include results of investigations obtained during last two decades.

The numerical methods, especially these which are based on finite element methods (FEM) have been very popular during the last decades. The FEM can be particularly useful for identifying the patterns of deformations and stress distributions in and around the RS structure under service loading. Very often, professional software is used to study the behavior of the RS structure. Its practical implementation is rather easy and achieved results can be presented in an attractive form. However, typical numerical procedures include significant idealizations od the solved problems. The main ones deal with geometry of the construction, load application and material properties. Therefore, each theoretical model should first be carefully verified on the basis of experimental results.

1.2 *Main conclusions from review state-of-the-art*

The design methods of the RS structures commonly used in practice are focused on their ultimate limit states. However, sometimes, for example during design of bridge abutments, the service limit state (SLS) should also be taken into account. In these cases accurate prediction of the RS deformation is crucial in design procedures. Although a number of different methods has been proposed, there is no one obviously acceptant methodology which should be used for calculation. The widely used analytical methods for estimating the maximum displacement of the RS walls are presented in the previous paragraph. All of them have strengths and weaknesses. Generally, these particular methods are based on rather simple mathematical equations and their use does not require special mathematical/numerical background. However, the most popular methods have been known for 20-30 years (the prevailing methods were proposed in the 90s of the 20th century). Therefore, the proposed solutions do not take into consideration the progress in the field of investigation of the RS structures behaviour which took place in the meantime. For example, very few available methods address the influence of facing rigity or creep properties of reinforcement material on the RS structures deformation (Kazimierowicz-Frankowska 2003). Moreover, some of the commonly used methods (especially the FHWA method and Jewell-Milligan method) are rather conservative and values of deformation obtained by using them are strongly overestimated (Khosrojerdi et al. 2017). Therefore, the problem of finding the method enabling very accurate prediction of the RS structures scope of deformation under serviceable loadings is very important from the practical point of view and needs further investigation.

2 PROPOSED ANALITICAL APPROACH

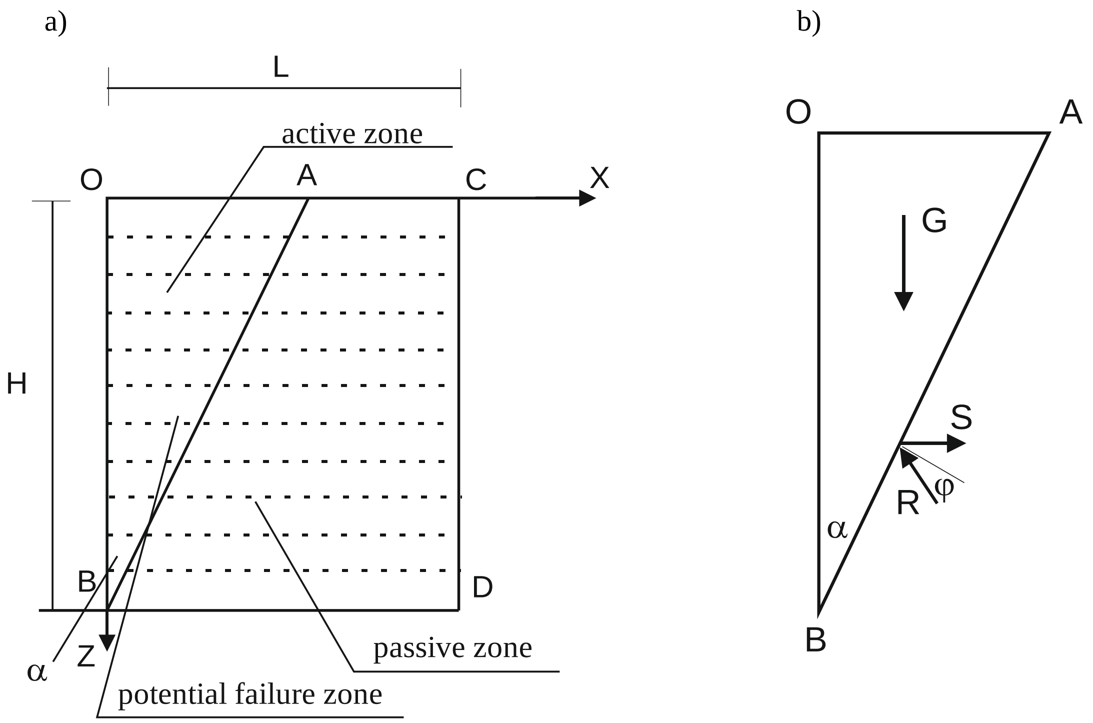
2.1 *Model of the RS structure*

The mechanics of the RS structures has been developed in IBW PAN for years. As part of the professional activity in this field the model of the RS was proposed by Sawicki (2000), which was later developed and verified on the basis of experimental results by Kazimierowicz-Frankowska (2003) and Kulczykowski (2013). The model presented has been successfully used for prediction of the RS structures deformation. It is based on the following principles:

- Cross-section of the typical RS wall with cohesionless backfill is considered in the analysis - Figure 2.
- A potential mechanism of failure is defined by the planar rupture surface AB, inclined at the angle θ to the horizontal. Two parts of the reinforced zone are selected: the triangular portion ABO, (denoted as the active zone in Figure 2a) and the quadrilateral portion ACDB (denoted as passive zone).
- The wedge ABO remains in the global equilibrium schematically shown in Figure 2b (the case of self-weight stresses). Adopting some simple assumptions one can determine the distribution of forces in the reinforcement, across the potential failure surface AB, corresponding to the global reaction of the reinforcement S (Sawicki 2000).
- Generally, the horizontal displacement (u_x) of the RS structure's facing consists of two parts:

$$u_x = u_{act} + u_{pass} \tag{1}$$

where u_{act} is the displacement resulting from the deformation of the reinforcement in the active zone and u_{pass} is the displacement resulting from the deformation in the rigid (passive) zone (caused by pull-out). However, in the case of perfect bonding horizontal deformation, it is caused only by displacement of reinforcement in the active zone.



$\alpha = 45^0 - \varphi/2$, φ = angle of internal friction of soil

Figure 2. Model of RS structure (a) and a global equilibrium of failure wedge (b).

In the case of reinforcement working in the elastic range, the strain in the active zone is calculated from Hooke's law:

$$\varepsilon_{act} = F/E \tag{2}$$

where $F = A_r \sigma_X^r$ - force in the reinforcement, $E = A_r E_r$ - elastic stiffness of the reinforcement, A_r - cross sectional area of reinforcement.

The horizontal displacement of the RS facing due to elastic deformation of the reinforcement in the active zone is calculated by the integration of strains:

$$u_{act} = \int_0^{x^*} \varepsilon_{act}\, dx \tag{3}$$

where x^* is the reinforcement length in the active zone $x^* = (H - z) \tan \alpha$

The second part of the horizontal displacement is caused by the reinforcement's pull-out from the passive zone. Respective formulae enabling the prediction of this kind of deformation are presented by Sawicki (2000) and Kazimierowicz-Frankowska (2003). In the latter, one can find solution for the case when creep of viscoelastic reinforcement is also taken into consideration. Here, due to strong volume limitation of the paper, only the final formulas will be presented. They can be used for prediction of maximum deformation of the RS structures with and without external loading. It is assumed that (as suggested by experimental results) the largest displacements occur in the top layers of the RS walls.

2.2 *RS structure without external loading*

The following input parameters should be determined before starting the calculations:

- geometrical quantities: height of the RS structure (H); length of reinforcement (L); vertical (ΔH) and horizontal (ΔB) spacing of reinforcement; width of reinforcement strip (B)
- material characteristics: tensile strength of reinforcement (R); stiffness of reinforcement (E); coefficient of friction between the soil and reinforcement (μ); unit weight of soil (γ); angle of internal friction of soil (φ)
- acting forces: type and magnitude of external load (P).

Taking into consideration the initial assumptions presented in the previous section and after mathematical analysis, the following formulas are obtained to calculate maximum deformation of the RS structure:

- for the case of perfect bonding between the soil and reinforcement (displacement resulting from the deformation of reinforcement deals only active zone):

$$u_{act} = \omega\gamma z(H - z) = -\omega\gamma\left(z^2 - Hz\right) \tag{4}$$

where $\omega = \frac{tan^3 \alpha}{E}\Delta H$

- for the case when horizontal displacement (u_x) of the RS structure's facing consists of two parts (displacements in the active and passive zones) because the bond-failure in the upper part of structure is possible:

$$u_{act} = \frac{\omega\gamma\Delta H\ tan\ \alpha}{E}\left[H(L - H\ tan\ \alpha)z - (L - 2H\ tan\ \alpha)z^2 - z^3\ tan\ \alpha\right] \tag{5}$$

and

$$u_{pass} = \frac{\sigma_r\left(1 + e^{-2\beta l}\right)}{\beta E\left(1 - e^{-2\beta Bl}\right)}\Delta H \tag{6}$$

where $\sigma_r = \omega\left[\gamma(L - h\ tan\ \alpha)z + \gamma z^2\ tan\ \alpha\right]$, l =length of reinforcement in passive zone, $\beta = \sqrt{\frac{2BG}{E}}$ = coefficient, G – coefficient (interface stiffness) which is determined experimentally; G is usually in the range between 10^3 and 10^4 kN/m^3.

2.3 *RS structure subjected to external loading*

The same input parameters are needed as in the previous case. They should be determined before calculation. In the case when perfect bonding between the soil and reinforcement layers is assumed, the horizontal displacement of facing is caused only by deformation in the active zone and can be calculated from the following formula:

$$u_{act} = \frac{\Delta H\ tan^3\ \alpha}{E}(p + \gamma z) = -\omega\left[\gamma z^2 + (p - \gamma H)z - pH\right] \tag{7}$$

In the second situation, when bond-failure of the upper reinforcement layers is possible, the maximum horizontal displacement (u_x) of the RS structure's facing consists of two parts (displacements in the active and passive zones):

$$u_{act} = \frac{\omega\Delta H\ tan\ \alpha}{E}\left\{\begin{array}{l} pH(L - H\ tan\ \alpha) + \left[p(2H\ tan\ \alpha - L) + \gamma H(L - H\ tan\ \alpha)\right]z - \\ \left[p\ tan\ \alpha + \gamma(L - 2H\ tan\ \alpha)\right]z^2 - z^3\gamma\ tan\ \alpha \end{array}\right\} \tag{8}$$

and

$$u_{pass} = \frac{\sigma_r\left(1 + e^{-2\beta l}\right)}{\beta E\left(1 - e^{-2\beta Bl}\right)}\Delta H \tag{9}$$

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3 VERIFICATION OF THE ANALYTICAL MODEL

The aim of the analysis presented here was to compare the maximum lateral deformation of the RS structures obtained experimentally and with the use of two different theoretical methods (FHWA method and method developed in IBW PAN). The selected results of experimental investigations performed in the full-scale were used to verify the theoretical approaches (see Table 2).

Typical results of calculations are presented in Table 3. They confirm the fact that the FHWA method is rather conservative. Using it for calculations caused strong overestimation of real deformation observed in the RS structures. Therefore, if a more accurate design procedure is needed other method of estimation should be found. One of the alternative propositions may be the model developed by research team from IBW PAN. The first results of its verification are promising. The IBW PAN method has relatively high accuracy and can be used for prediction of different structures' behavior.

Table 2. Experimental data which was used for verification of the accuracy of theoretical prediction.

Case number	References	Basic input parameters
1	Hatami & Bathurst (2005) - wall no. 1	H=3.6m;L=2.5m; ΔH =0.6m;R=20.4kN/m; E=476kN/m^2; φ =40^0; γ =16.8kN/m^2
2	Bueno et al. (2005)	H=4.0m; L=3.0m; ΔH =0.4m; R=13.0kN/m; E=13kN/m^2; φ =32^0; γ =18.0kN/m^2
3	Hatami & Bathurst (2006) – wall no.5	H=3.6m;L=2.5m; ΔH =0.6m;R=17.5kN/m; E=153kN/m^2; φ =40^0; γ =16.8kN/m^2
4	Benjamin et al. (2007)	H=4.0m; L=3.0m; ΔH =0.4m; R=14.3kN/m; E=13kN/m^2; φ =33^0; γ =18.0kN/m^2
5	Bathurst et al. (2009)- wall no. 2	H=3.6m;L=2.5m; ΔH =0.6m;R=10.2kN/m; E=238kN/m^2; φ =40^0; γ =16.8kN/m^2

Table 3. Predicted and measured maximum lateral deformation of the RS walls

Case number	Experimental Results (mm)	Calculation results (mm)		Important information
		FHWA Method	IBW PAN Method	
1	5.2	48.4	6.5	results at the end of construction
	9.3	68.0	16.1	results under external loading p=30kPa
	13.5	80.8	22.4	results under external loading p=50kPa
	31.4	93.5	28.9	results under external loading p=70kPa
2	15.7	50.6	20.9	results at the end of construction
3	10.5	68.0	22.4	results under external loading p=30kPa
4	12.2	50.6	21.0	results at the end of construction
5	7.9	48.4	10.4	results at the end of construction
	12.0	68.0	31.1	results under external loading p=30kPa
	35.0	80.8	44.9	results under external loading p=50kPa
	58.4	93.5	58.7	results under external loading p=70kPa

4 CONCLUSIONS

The main purpose of this paper was to summarize knowledge about methods commonly used to calculate deformation of the RS structures and to propose alternative methodology which has been successfully developed for years by research team from IBW PAN.

The review of state-of-the-art shows that modelling and prediction of the RS structures deformation is one of the most complicated tasks in their design procedures. Currently, there is no generally accepted theory for describing and solving this problem. This gap in technological standards should be filled because the scope of deformation is very important from engineering point of view and failure of selected types of the RS structures (e.g. bridge abutments) is often defined as exceeding tolerable deformation.

Commonly used methods are rather conservative. Moreover, they are not really new (most of them were proposed in the 80s-90s of the 20th century). Therefore, they don't take into consideration all factors/parameters which strongly influence the RS structures deformation. For example they very often neglect to account for the effect of facing rigidity and creep properties of materials used as reinforcement. It may cause significant errors between predicted and measured values of deformation (Khosrojerdi et al. 2017).

More accurate prediction of the RS structures behavior under serviceable loading needs further investigation including both experimental and theoretical work. One of the alternative approaches to modeling deformation of the RS structures is presented in this paper. Although the obtained results are far from being exhaustive, the first results of verification of the accuracy of IBW PAN method are promising. The research will be continued in the next future.

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