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3D Approach of Arching Effect in Basal Reinforcement Layer

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Abstract

Several analytical and numerical models have been introduced and tested to assess the arching effect on piled embankment. Given the prevalence and popularity of this case, it is not easy to select and recommend best design methodology. Used materials and types of reinforcement play an important role when it comes to designing high-speed railway lines in difficult geological conditions. Our numerical approach by 3D FEM analysis was focused on the influence of geometry to the arching creation in basal reinforcement layer, especially to distribution of internal forces in high tensile geogrids.

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Keywords: basal reinforcement; arching effect; numerical model; piled embankment.

1. Introduction

Geotechnical engineers of high-speed railway lines or motorways in the area of problematic geological conditions don't have it easy choosing the right solution that would the most appropriate to use for overcoming all the risks and difficulties of weak subsoil at the site. In the past years, solutions have represented using massive exchange of weak soil till bedrock or stiff layer, but new technological solutions have appeared with the emergence of geosynthetics. These new solutions include the creation of reinforced embankments on compressible soil using basal reinforcement layer in contact, which is used to transfer the load from the embankment into the pile supporting system, Fig. 1. This type of structure was first used in central Scotland in 1973, [1]. Currently, the only official standard for piled embankments is BS 8006 [2]. Other documents represent design recommendations, such as Ebgeo [3] or Dutch method [4], which are certain variations and improvements of the original design methodologies. Since then, several other applications have been realized, also in Slovakia at high-speed railway line near "Turecky vrch" tunnel, [5, 6].

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These solutions are, in principle, more expensive and more complicated and the appropriate design proposal must also include local influence and risk. Variation of the pile material and diameter is possible in the pile support system, but generally, there is no room for significant savings in the solution, rather they are simplifying the previous technological potential damage and poor quality production during realization. The total weight of the embankment with the traffic load must be transferred by a certain number of supporting piles. Appropriate use of materials from local sources and determining the ratio between soft subsoil support and reinforcement support at the part of unbearable subsoil between the piles are important elements to consider, [12]. This correct assumption, estimation and calculation help obtain savings of reinforcement material over the pile heads, Fig. 1.

1.1. Piled embankment structure

Reasons for building up piled embankments on high-speed railways lines are to overcome complicated engineering geological conditions.

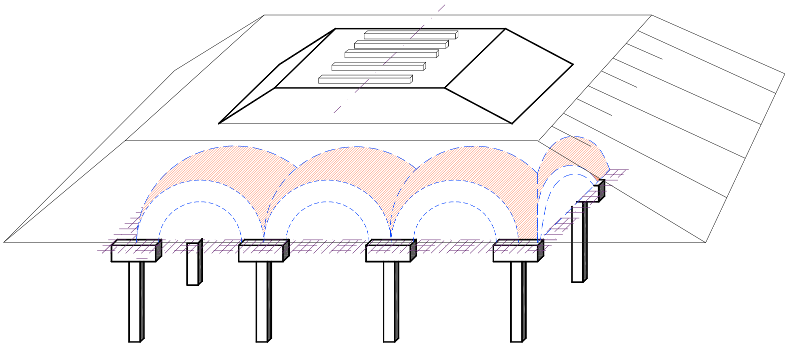

Fig. 1. Piled embankments with arching effect.

Many authors have brought the proposal along with some improvements and recommendations to the piled supporting structure and a basal reinforcement layer over subsoil. Our contribution is to address the impact of geometry and distribution of the supported piles in the 3D model on the necessary tensile forces in basal reinforcement layer.

1.2. Design methodology

After building up piled embankment, weak subsoil will consolidate, which can cause differential settlement of subsoil and relatively stiff piles. If there is a movable piles support, partial transfer of load is done by soft subsoil support at surface layer, but difference between stiffness and deformation resistance activate tensile forces in basal reinforcement layer. Embankment material sits naturally over piles that are bored or even drilled. Redistribution of vertical and shear loads due to unequal support, which causes concentration of stress above the heads of piles, is called "arching effect". The design of piled embankment consists of many partial design proposals and evaluation in both possible limits states. There are not so many differences in pile support arrangement and single pile bearing capacity evaluation. When focusing on details, the main differences are in theoretical approach of 3D effect of arching. These proposals have significant influence on calculated long term design tensile strength. When we compare different approaches, interesting differences are in distribution of tensile strain in geogrids laid on pile cap. Some authors have introduced a simplified view of the whole load (embankment and the traffic load) which is transmitted through the vertical support bearing elements (piles of any type, concrete, wood, CFA piles, gravel piles, stone column, etc..) directly into the subsoil. The greater part of the load is directly transferred by creating arching onto the pile heads. Even though the arching is formed, it is necessary to transfer excess load directly to the piles. This transfer is done by horizontal geosynthetic reinforcement. A survey of various projects found that the percentage of area coverage by pile heads is 60% to 70%, which can be reduced to 10% to 20% by properly designed horizontal reinforcement. This can, if necessary, achieve a tensile strength up to 900 to 1 350 kN/m, [4].

Designing piled embankments can be divided into several parts, [7, 8]:

- calculation of the vertical load carried by the piles and reinforcement due to the creation of arching effect,
- proposing the necessary number of piles and their distance depending on their number,
- determination of the tensile stress in the reinforcement at the vertically loaded part between piles,
- tensile stress calculation in the reinforcement due to horizontal load at the part of slope of embankment.

The important part is a correct assumption and calculation of the vertical load carried by the reinforcement between piles.

2. The theory of the arching support

2.1. Guido method of arching

- The main feature is reinforcing basal layer over piles with multiple layers of geogrids (GGR) of low strength, with no support from the subsoil, see Fig. 2. (a).
- The creation of the pyramid of height 0.5(s-a) at angle 45° from the edge of the pile head, where the angle of internal friction φ of fill material is neglected.

2.2. Assumptions of the Swedish method

A simple 2D analytical model, more realistic than "Guido Method" [9],

- Basal layer is reinforced with one geogrid (stronger than used in the "Guido method").
- Reinforcement design is based on the "membrane theory" similar to the BS8006 (1995).
- The analytical model was not confirmed by physical modelling results, therefore the original model was modified into a 3D form as an inverted - truncated pyramid. Support of subsoil is not counted in the model.
- The creation of pyramid of height 0.5(s - a).tan(75°) at the angle 75° from the edge of the pile head, the angle of internal friction φ of fill material is not taken into account.
- Slightly modified form of the "3D arching" model was adopted [10].

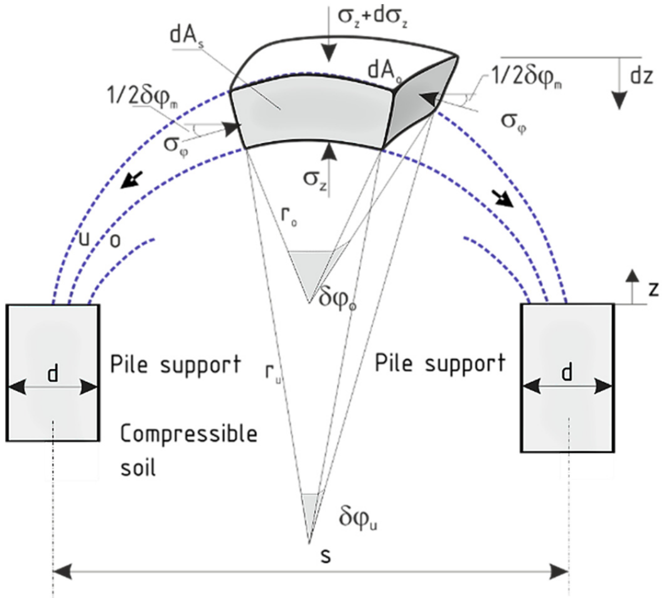

Fig. 2. Arching effect on the piled embankments, [9].

2.3. British Standard 8006

The first approaches were explained and described by John (1987) [11], further development was published by Jones et al (1990) [11], set up as a standard in 1995 and revised in 2010 [2], with following principles:

- It is a more sophisticated approach than "Guido method" and the "Swedish method".
- 3-D general assumption in the embankment is always a half-sphere - Fig. 2. (b), which does not depend on quality of filling material (the same results for fine sands and crushed stones, which is not realistic).
- Membrane theory for the tensile forces calculation in the reinforcement, reinforcement is concentrated in one or two layers directly laid on piles heads. No support from the subsoil - it is on the safer side and free-hanging system, BS8006 (1995) took over the results of the physical modelling of similar structures.
- John (1987) [11] adopted 2D arching approach and modified it to the 3D suit conditions.
- Russell and Pierpoint [8] pointed out the inconsistencies in some arching solutions given in BS8006: 1995.
- BS8006-1: 2010 [2] design method has been very little modified and has stood the test of time and provides conservative (i.e. safe) designs.
- The revised section of BS8006: 1995 of „Basal reinforcement of piled embankments" was supplemented by

Hewlett and Randolph assumption [13], which better represents the "real" 3D arching mechanism.

2.4. German methods

The first development began in the years 1992-1993 in parallel with the known draft of BS 8006, with principles:

- Redistribution of stress in the embankment regardless of shear strength, which was estimated in the "Guido method", "Swedish method" and BS 8006 draft was not accepted by geotechnical engineers in Germany.
- It was decided that to combine stress-redistribution by Hewlett and Randolph (1988) assumption, which for the first time includes the impact of angle of friction of fill material along with a "membrane theory" according to [2]. The thickness of the arching shell is $b/\sqrt{2}$; where b is a width of supported pile/head.
- Further efforts to correct errors in [13] were made and the carrying capacity of the soft soil between piles (upward counterpressure of soft soil between the piles) and basic recommendations for minimum reinforcement strength were taken into account.

New German method development began around 1996:

- Main idea was to improve the redistribution theory of stress in the embankment and to find a way of considering a partial soil support, acting from counterpressure of soil between the piles.
- The "new" German approach adopted multi-shell arching theory [14], which was subsequently developed, [11], see Fig. 3.(c).
- The main characteristics are: a new "multi-shell" arching theory, calculation of tensile forces in the reinforcement with regard to its short-term and long-term modulus of elasticity and oedometric modulus of soft soil, stress related to counterpressure; recommendation to use a maximum of one or two layers of high-strength reinforcement at the top of the pile instead of a more low strength reinforcements. In any case, the minimal design tensile strength must be ≥ 60 kN.m^{-1} in both directions.
- The crucial moment is in consideration of whether the back pressure can be guaranteed through the whole design lifetime, for example 100 years, since the subsoil surface can settle due to possible decreasing of ground water or consolidation, which results in free hanging system "in the air".

2.5. Dutch CUR 266 method

Dutch approach based on EBGEO [3] is currently the most sophisticated design recommendation, because of recognition of disadvantages of previously described methods and current research, [4]. Calculation is performed in following steps:

- Average pressure on the geogrids must be calculated first, then in its second step EBGEO uses a triangular pressure distribution on geogrid. This assumption following from [3] was not confirmed by other researches, such as physical or numerical modelling. Van Eeckelen [11] showed that the measured pressure distribution on the reinforced geogrid strip between the piles can be better approximated with an *inverse triangle*.
- Then was developed the new model as an extension of Hewlett and Randolph's model [13] and EBGEO [3] models, and called it a "concentric hemispheres model", [11]. The main principle is based on extension of the arch downwards to the subsoil, resulting in a set of concentric hemispheres. These hemispheres apply a force on their subsurface. The larger the radius, the larger force acting on the subsurface.

2.6. 2D vs. 3D approach

Generally 2D analytical solutions are simpler and more fitting for basic design, [10]. When we use uniaxial geogrid of high tensile strength for reinforcement in two directions, then contribution of reinforcement in perpendicular direction is not considered, and this is safer solution. The same situation can appear in 3D analytical solutions. Implementation of detailed reinforcement into numerical 3D model requires special procedure and verification. In the case of vertical stress calculation, Zaeske [14] introduced 3D analytical solution of arching creation, Fig. 3.

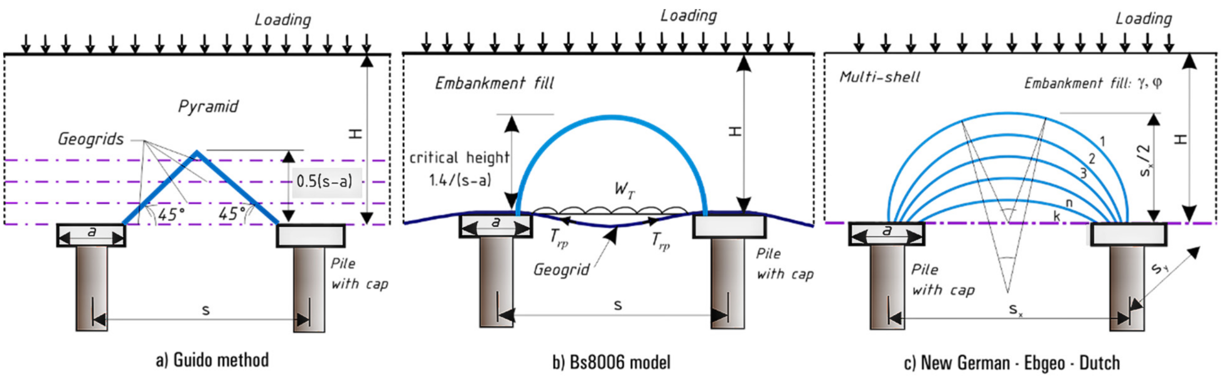

Fig. 3. Multi-shell theory of 3D arching for piled embankments, [14].

The element of arch is in vertical equilibrium and can be described by differential equation:

$$F_v = (\sigma_z + d\sigma_z)\cdot dA_0 - 4\sigma_\varphi \cdot dA_s \cdot \sin\left(\frac{\delta\varphi_m}{2}\right) + \gamma \cdot dV - \sigma_z \cdot dA_U = 0; \quad (1)$$

where: $(\sigma_z + d\sigma_z)\cdot dA_0$ is a pressure acting on the top of arch, $4\sigma_\varphi.dA_S.\sin(\delta\varphi_m/2)$ is a shear friction on the four sides of the element, $\gamma.dV$ is a self-weight of element and $-\sigma_z.dA_U$ is a bearing reaction below arch.

Different arching approaches lead to different stress distribution and cause different tensile forces in reinforcement. Hewlet and Randolf [13] have introduced a formula used by BS, symbols are presented on Fig. 2. (b):

$$T_{rp} = \frac{W_T.(s-a)}{2.a}.\sqrt{1+\frac{1}{6.\varepsilon}} \quad (2)$$

Ebgeo [3] and Dutch CUR 2010 [4] recommend calculating tensile forces due to vertical load of geogrid between piles T_v with simple equation:

$$T_v = \varepsilon \cdot J = \varepsilon \cdot EA_g \quad (3)$$

where ε is an average strain in the geosynthetic reinforcement and EA_g is a stiffness in calculated direction (x, or y). Ebgeo recommends using stiffness according to limit state or derived from laboratory testing.

3. Numerical comparison

A simple model of piled embankment (γ = 18 kN/m^3 φ = 32°, q = 20 kN/m^2) of height of 4.0 m supported by embedded piles of diameter 300 mm, at basal layer reinforced by a single layer of geogrid has been created. Following table presents results of 3D FEM model in comparison with analytical approaches by BS and Ebgeo calculation. For demonstration of differences, pile distance in square net was varied from 1 to 3 m.

4. Conclusions

Designing piled embankment structures is an interesting topic, which requires further verification by numerical and physical modelling. Importance of complexity of this structure confirms that in simple models without piles or without geogrids deformations are not accepted. Presented analytical models of design piled embankments were commented and evaluated. Significant improvement of Ebgeo was proposed in CUR 266 by Van Eeckelen [11] while BS 8006 standard is in safer side of design than Ebgeo. Nowadays, the most sophisticated approach is 3D model by FEM analysis, which requires skills and verifications of engineers. Presented calculated results (Tab. 1.) show differences according to arching theory and confirm passive design of BS standard. Required tensile strength depends strongly on supposed strain in the analytical calculations. Numerical models and laboratory models indicate lower strains in geogrids than what is recommended by analytical solutions.

Tab. 1. Results of numerical model of piled embankment compared with analytical solutions.

	Numerical model 3D					BS8006			EBGEO		
Pile's spacing	Load on the pile	Axial force in GGR	Reinforc. deflection below the base	Vertical stress on subsoil at base	Tensile force in GGR	Load on the pile	Vertical stress on subsoil at base	Tensile force in GGR	Load on the pile	Vertical stress on subsoil at base	Tensile force in GGR
[m]	[kN]	[kN/m]	[mm]	[kN.m^{-2}]	[kN/m]	[kN]	[kN.m^{-2}]	[kN/m]	[kN]	[kN.m^{-2}]	[kN/m]
1	141.89	1.257	1.9	5.5	6.13	38.69	14.63	61.71	29.7	67.71	11.35
2	177.91	1.55	3.1	19.89	20.02	142.46	83.07	471.56	49.63	81.03	34.04
3	219.32	2.4	5.4	15.8	38.57	312.9	202.2	1082.2	69.51	84.94	113.45

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