Numerical simulation of soil nailed retaining systems with geosynthetic reinforcement as the facing support

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ABSTRACT: This research numerically examines the stability of a bridge abutment reinforced with grouted nail with geosynthetic facing in service and ultimate load states. Recently, soil-nailing technique has become a widely accepted method to efficiently reinforce the in-situ earth retaining systems. Although, the face of the retaining systems is very often supported by reinforced concrete elements, recent advancements in geosynthetic reinforcements have shown a potential to use geogrid as the face support for earth retaining structures. However, using different types of reinforcing elements in a single system results in complex soil-reinforcement interactions. With advancements in computational capacities, numerical simulation methods have become popular to assess the performance and the stability of geostructures. Despite the popularity of the computational methods for geosynthetic reinforced systems, there is still a debate on appropriate type of elements to simulate reinforcing members and their effects on the numerical predictions. The main difference between the various types of numerical elements (i.e. beam and geogrid elements) is considering the contribution of bending and shear resistances of nails and face support elements to the deformability and stability of retaining system. Several studies indicated that ignoring the influence of bending and shear resistances result in slight conservatism. However, the influence of such assumptions on the global ultimate stability of the system and safety factor has not received sufficient attention. Therefore, this research aims at evaluation of numerical results for retaining soil structures reinforced by grouted nail and geosynthetic materials under service and ultimate loads for a complex system that consists of pile, grouted nails and geogrid face support.

Keywords: Numerical simulation, soil nailing, georgic face, support structural element

1 INTRODUCTION

With a significant growth in the urbanism, deep excavations, extension of highways and bridges and construction of the high slopes and retaining structures have become extensively popular. Despite the simplicity of the soil nailing as a flexible retaining stabilization technique, there is still a debate how to consider the contribution of the structural nail elements in the different design methods which are available for slope stability analysis. To analyze the geotechnical slopes, numerical tools have been well developed on the basis of limit equilibrium and limit analysis to find the collapse load in the systems; however, these methods have significant limitations such as disability to find the exact solution, the need to predefine the slip surface among the others while these issues have been overcome in the recent numerical packages for stability analysis (Lavasan et al., 2017a). Nevertheless, the still remaining aspects in those solutions are (a) how to address the non-linear interactions between the soil and structural elements in those classical solutions, and (b) how to define the deformations in the system and how to consider the impact of the pre-failure deformations on the failure loads (Lavasan et al., 2017b).

In last 3 decades, the finite element and finite different packages have been developed and commonly used to solve the complex geotechnical problems including the geometrical and material nonlinearities. These packages can be employed to determine the pre- and post-failure deformations and accurate ultimate collapse load that is consistent with the deformations. To determine the ultimate loads, finite element limit analysis (FELA) or strength reduction finite element analysis (SRFEA) cab e carried out assess the performance of the system at the ultimate load state (ULS). The SRFEA techniques (ϕ-c-reduction)

are widely used in practice for calculating factors of safety (FoS), however, Potts and Zdravkovic (2012) offer alternative procedures. The Dutch design guideline CUR 226 (van Ekelen and Brugman, 2016) proposes a framework in order to incorporate FELA in accordance with both characteristic and design values of the strength and loads for ULS analysis of geotechnical systems with structural elements.

Despite of this transparent approach for the calculation, there is still a long-lasting debate on whether or not the shear and bending stiffness and resistance of the very slender individual structural elements (e.g. nails) should incorporate into the calculations (Juran et al., 1990; Schlosser, 1991; Jewell and Pedley, 1992; Shiu et al. 2006; Fan and Luo 2008; Babu and Singh, 2009). A literature review shows that both geogrid and beam elements have been employed to numerically simulate the nail structures (Liew and Khoo 2006; Babu and Singh 2007; Fan and Luo 2008). Using the appropriate type of the structural element becomes more crucial when the flexible geogrid element with high tensile stiffness is supposed to be used as the facing of the nailed slope.

In this study, the influence of the type of the element in accordance with adopting or ignoring the shear and bending stiffness on the model response of a complex system is investigated. The geometry of the problem and the properties of the materials are taken from a project in the Netherlands.

2 NUMERICAL ANALYSIS

The project studied here deals with a bridge abutment foundation in which the dead and live loads (e.g. the weight and the traffic load) are transferred from the bridge deck to the concrete bank seats that are supported by a twin-battered pile system. The embankment underneath the bank seat had an initial slope of 2H:1V, however, it was planned to be cut to the slope of 1H:5V. In order to avoid instability in the slope, the exiting slope is first cut to the slope of 1H:1V. Afterwards, the slope is nailed and then the rest of the slope is cut to the final slope of the retaining structure. After cutting the slope to the expected slope, the retaining structure with the height of 4.5 m is covered by flexible geogrid, the bearing plates are installed and the nails are fixed. At last, the face of the slope is covered with a uniform concrete block that stands on its foundation with no contact to the nailed slope. The schematic shape of the problem at the beginning and end of the construction is shown in Figure 1.

| (a) beginning of construction | (b) end of the construction |
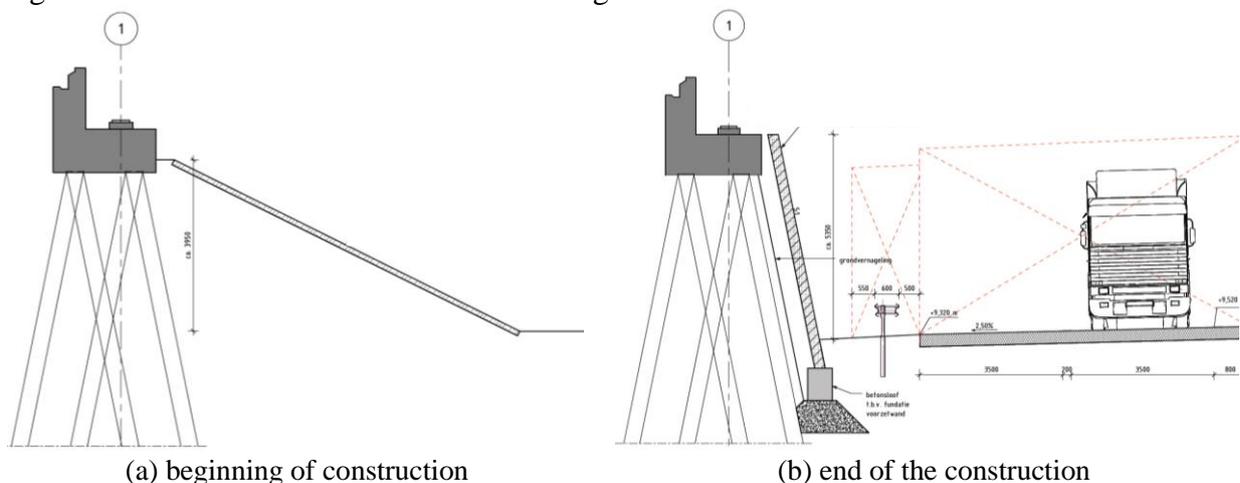
Figure 1. The initial and final geometry of the problem

The finite element (FE) calculation has been carried out by the use of *PLAXIS*[2D] numerical package. The analyses aimed at investigating the deformability of the system and variation of the structural forces in the piles, grouted nails and geogrid facing through the construction of the nailed wall. In the analyses, two-dimensional numerical simulation is carried out in accordance with the plane strain condition. The design has been performed based on update of the Dutch guideline CUR 226 (van Ekelen, 2016). In this guideline, the most relevant approach for the finite element based ULS analysis is known as the calculation using the characteristic values for the soil strength and loads along with low characteristic stiffness of soil and structural element. The required calculation phases should be analyzed using design values for both soil and loads. The design parameters defined by adopting the reduction factors for the soil parameters and loads with respect to the CUR 226. To assure realistic simulation of the problem, the construction phase is simulated using the characteristic values of the loads, strength and stiffness for soil and structural elements. At the end of construction, the service and ultimate load analyses (SLS and ULS) are carried out in accordance with the characteristic and design load and strength, respectively. The calculation phas-

es are introduced in Table 1 and graphically illustrated in Figure 2.

Table 1. Description of the calculation phases in construction stages and analysis

Phase	Description of phase	Phase	Description of phase
# 1	Initial arrangement	#7	4th step exaction (slope 5:1)
#2	Cutting the slope to 1:1	#8	Concrete panel (cover) installation
#3	Nailing the entire system (slope 1:1)	#9	Refilling the panel base
#4	1st step of excavation and covering	#10	Service Load Analysis
#5	2nd step excavation and covering	#11	Ultimate Load Analysis
#6	3rd step excavation and covering		

phase #1 phase #2 phase #3

phase #4 phase #5 phase #6

phase #7 phase #8 phase #9
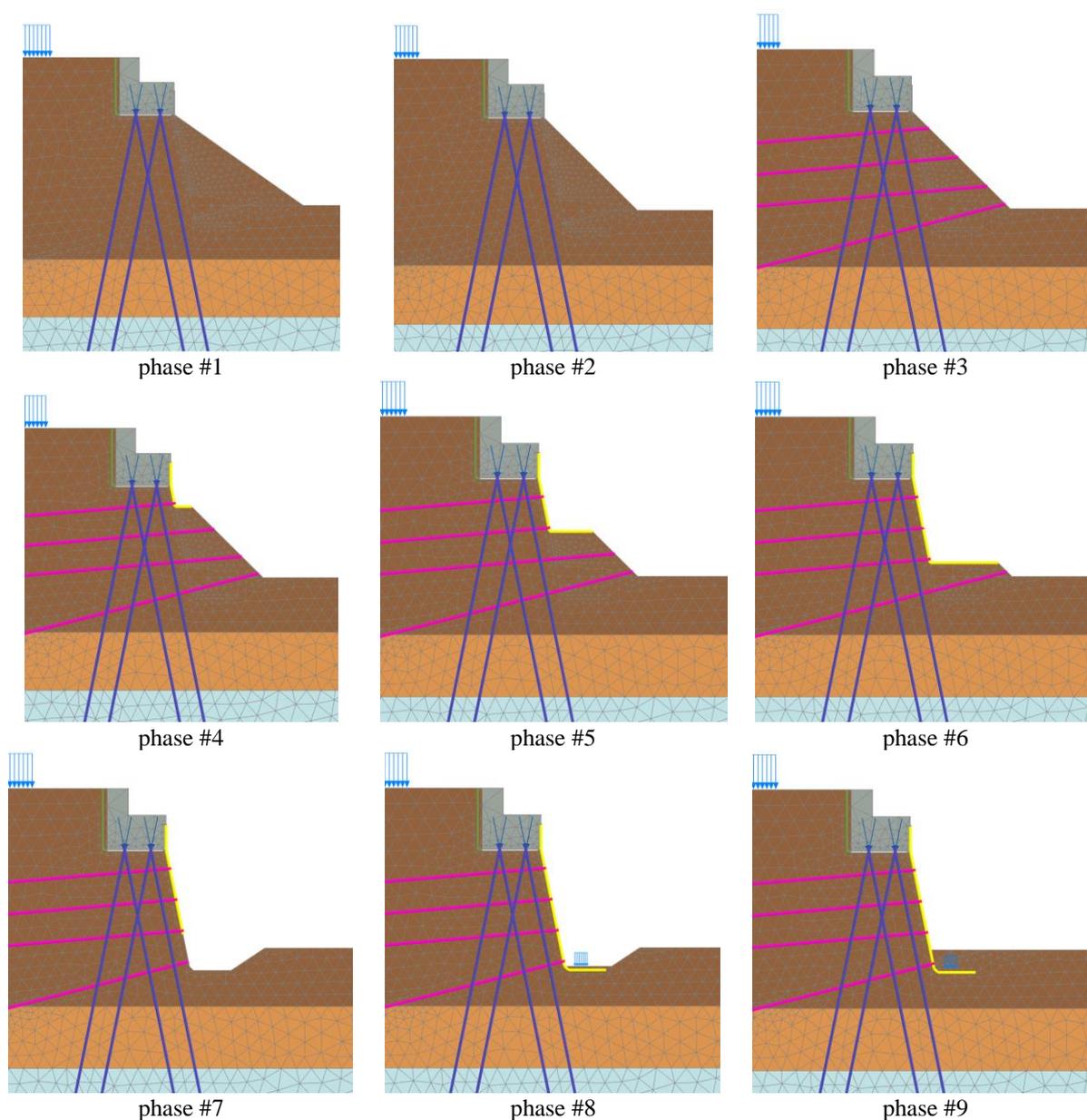
Figure 3. The schematic sketch of the construction phases in the numerical analysis

In order to idealize the 3 dimensional pile and nail elements into 2D, the concept of equivalent stiffness with reference to the spacing between elements along the axisymmetric axis has been taken into account. The precast concrete panel is expected to have no contribution to the stability of the slope and therefore only its weight is considered in the present calculations (Phase #8 in Figure 3). According to the geotechnical report, the soil stratum consists of 3 main layers as: (i) top soil (h=8.5 m), clayey sand (h=2.5 m), and sand (infinite). To simulate the soil behavior, Hardening soil small strain model (HSsmall) that is available as an in-built constitutive model in *PLAXIS* is adopted. The arrangement of the soil layers in the numerical model is shown in Figure 1. The ground water table is assumed to be lower than the in-

fluence depth of the system and the materials are assumed to be drained. The mechanical parameters of the soil in numerical simulation are shown in Table 2.

Table 2: Mechanical parameters of the soil employed in numerical simulation

Properties Material	$E_{oed.}$ (MN/m^2)	E_{50} (MN/m^2)	E_{ur} (MN/m^2)	G_{max} (MN/m^2)	$\gamma_{0.7}$ (%)	m (-)	c (kPa)	φ (deg)	ψ (deg)	R_{int} (-)	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)
Top soil	21.5	22.5	70.0	48.0	0.05	0.6	0.1	35	5	0.8	18	18
Clayey Sand	5.0	5.0	15.0	10.0	0.02	0.5	1	27	0	0.5	18	18
Sand	21.5	22.5	70.0	48.0	0.05	0.5	1	35	5	0.8	19	19

The concrete bank seat and the piles are simulated by linear elastic model along with non-porous drained material. The square-shaped battered concrete piles in the model have a size of 380 mm × 380 mm with a length of 13 m (inclination slope of 5V:1H) while the horizontal spacing between the piles is 1.65 m. The elastic modulus of the pile is taken as E_{cm}=36,000 MPa. The piles are simulated by the use of embedded beam structural elements.

The grouted nails consist of steel bars with diameter of 32 mm, the diameter of the drilling holes is 10 cm where the spacing between the steel bar and the drilled soil is filled with concrete grout. It has been assume that the nails are not pre-stressed. In the height of the slope, 4 nails are going to be installed in a vertical spacing of 1.25 m. The horizontal spacing between the nails (S_h) is assumed to be 1.65 m. To anchor the head of the nails, steel plates with the size of 10 cm × 10 cm having a thickness of 20 mm are utilized. In the numerical analyses, the grouted nails are simulated by the use of either beam or geogrid element where the end plates are simulated using plate element with equivalent stiffness per unit meter of the nailed slope. Considering the geometry of the nails and the horizontal spacing between them, the equivalent axial stiffness of the nail (beam or geogrid) and the equivalent thickness (for beam element) are defined to be equal to 115 MN/m and 8.66 cm, respectively. The equivalent axial and bending stiffness of the bearing plates are assumed to be equal to 242 MN/m and 0.81 MNm^2/m, respectively. In these calculations, the Young modulus of the steel and grout are assumed to be equal to 200E3 and 4E3 MPa, respectively. It is worthy to note that a full bond is assumed between the grouted nail and the surrounding soil by defining no interface at the contact between the nail and the soil. To avoid simulation of the bridge span and the corresponding interactions, the dead and live loads of bridge span are directly applied as point axial loads on the piles.

To confine the soil between the nails and to cover the face of the slope, a layer of polyester geogrid with a tensile strength of 0.3 MN/m is used where the geogrid layers are tied beneath the end plate. Since the deformations in the geogrid should be small, the tensile stiffness of geogrid is determined on the basis of the isochronous of the product to be equal to 2.25 MN/m.

In this numerical study, a series of trial analyses have been preliminarily conducted to define the most relevant size of the model and the proper discretization to ensure no influence of the boundaries and mesh size on the numerical predictions. It has to be noted that the updated mesh feature was activated in all of the numerical calculations in present study.

3   RESULTS AND DISCUSSIONS

In this section the outcomes of the numerical analyses of the system in terms of the contribution of the shear and bending stiffness of the nails on the deformations, failure mechanism and structural forces for the nailed soil structure are examined.

3.1   *Structural forces*

As the FE calculation is often utilized to estimate the forces in the structural elements, this section concerns about the structural forces for different numerical simulation technique. Figure 4 demonstrates the variation of the tensile force in the geogrid that used as the facing element for different numerical schemes and load state (e.g. ultimate or service). As seen in Figure 4, the tensile force in the facing element varies about 10% when the type of the element that represents the grouted nail in the earth structure in the numerical model. Apparently this difference can be mainly attributed to the contribution of the shear and bending stiffness of the beam element that is neglected in geogrid type of the structural ele-

ment.

(a) beam element-ULS
$F_{max.}$= 13.75 kN/m

(b) geogrid element-ULS
$F_{max.}$= 12.59 kN/m

(c) beam element-SLS
$F_{max.}$= 12.97 kN/m

(d) geogrid element-SLS
$F_{max.}$= 11.35 kN/m
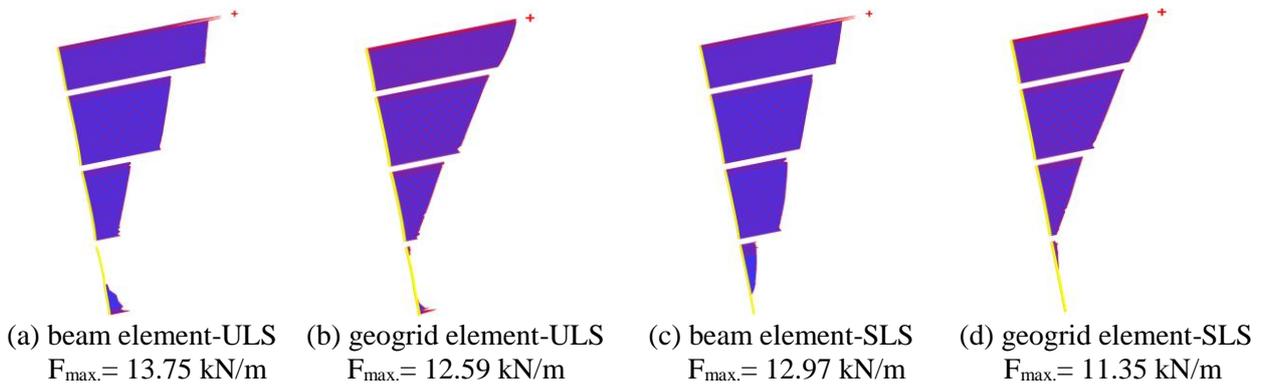
Figure 4. Tensile force in the geogrid facing element for nail simulated as
beam (bending element) or geogrid (no-bending element)

(a) beam element-ULS
$F_{max.}$= 46.79 kN/m

(b) geogrid element-ULS
$F_{max.}$= 43.47 kN/m

(c) beam element-SLS
$F_{max.}$= 28.68 kN/m

(d) geogrid element-ULS
$F_{max.}$= 25.05 kN/m
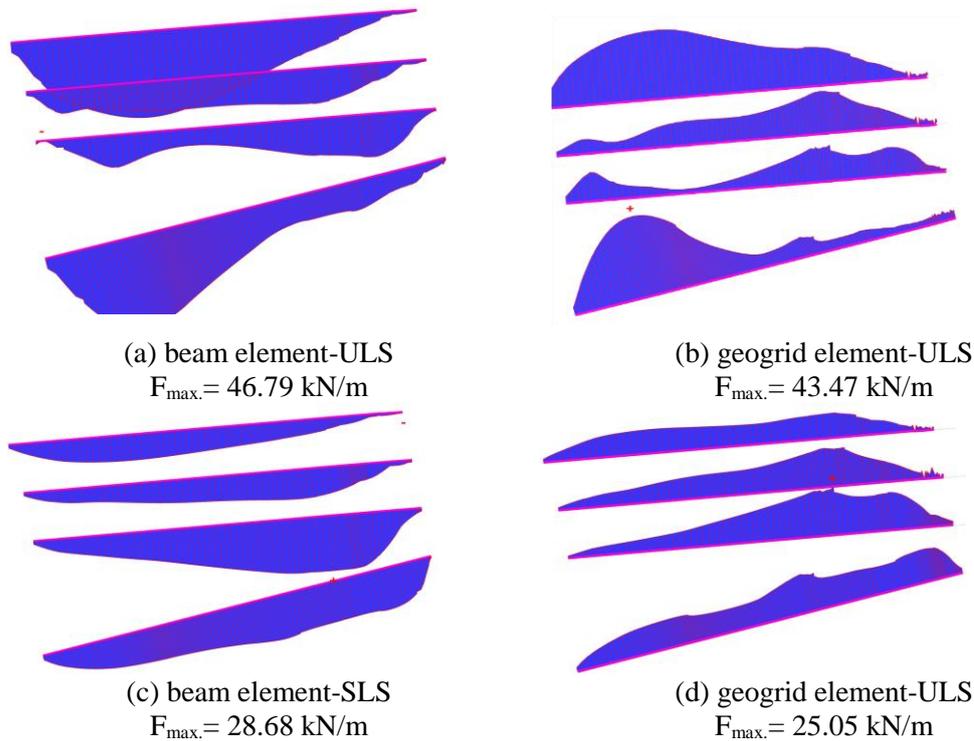
Figure 5. Distribution of the tensile force in the nails for nail simulated as
beam (bending element) or geogrid (no-bending element)

Figure 5 shows the distribution of the tensile force in the nails at various load states and for different types of the structural elements as the nail. As seen, though the distribution of the tensile force over the length of the nail is similar for identical load cases, the maximum loads and the position of the maximum tensile load are not identical. Additionally, the contribution of the shear and bending of the beam element causes about an overall 10% higher maximum tensile force in the nail. As seen, the location of the nails with higher tensile forces (i.e. the highest and lowest nails) is found to be at the identical for both types of the elements (e.g. beam and geogrid). Table 3 shows the maximum structural forces in the pile elements. It is to be noted that the maximum shear force in the deep piles is observed at the contact between the piles and the bank seat (head of the pile). However, the maximum bending moment takes place almost at the middle of the pile. According to Table 3, the type of the element that is used to model the nails significantly affects the shear force at the head of the pile. Apparently, the maximum bending moment in the piles is approximately 10% higher when the contribution of the shear and bending resistance of the nail is taken into consideration.

Table 3: Maximum structural forces in the piles

Load state	ULS		SLS	
Nail element	Shear force (kN/m)	Bending moment (kNm/m)	Shear force (kN/m)	Bending moment (kNm/m)
Beam element	907.5	235.3	907.4	224.7
Geogrid element	464.8	214.9	478.0	202.5

3.2 *Soil responses*

In addition to the structural forces in the battered piles, nails and geogrid facing, accurate prediction of the mobilization of the shear strength in the earth structure and the subsoil and the corresponding deformations in the face of the step slope are essential aspects. Accordingly, the state of the mobilized shear strength in the soil at different load states is reported for the cases where the nail is simulated as beam or geogrid element. Figure 6 shows the mobilized shear strength in the domain for different load cases.

(a) beam element-ULS   (b) geogrid element-ULS   (c) beam element-SLS   (d) geogrid element-ULS
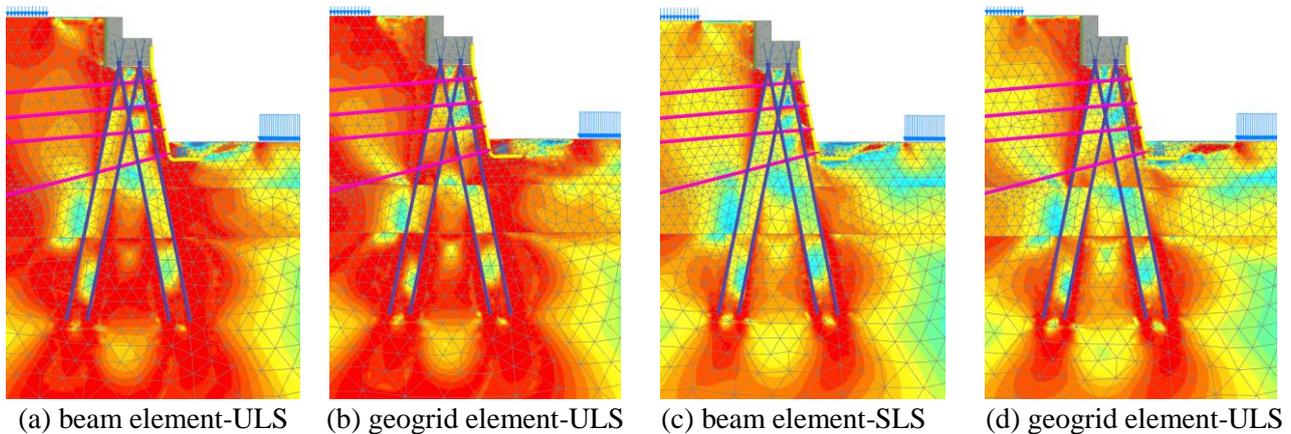
Figure 6. The mobilization of the shear strength in the domain (Red: 100%; Dark blue: 0%)

According to Figure 6, it can be seen that the nature of the mobilization of the shear strength in the domain is identical for comparable load cases. Apparently, for ultimate load state, the shear strength of the soil gets mobilized more significantly in a larger domain. As seen, the piles mainly act as end bearing elements that transfer the dead and live loads from the bank seat to the bearing soil layer. However, at the ultimate load state analysis (Figures 6a and 6b), the role of the skin frictional resistance of the pile becomes more dominant. Due to the important role of the deformations especially at the vicinity of the abutment face, the deformation for the slope surface is illustrated in Figure 7.

According to Figure 7, the difference between the deformations of the slope face for beam and geogrid elements as nails is not remarkable when the service load state analysis is concerned. However, the difference between the deformation predictions becomes more significant at the ultimate load analysis. As seen, the maximum face deformation at ultimate load state is obtained when the nail is simulated by the use of beam element that accounts for the contribution of the shear and bending resistance of the nails. Apparently, the most critical horizontal deformation of the wall is in the allowable range namely less than 10 cm at ultimate state and less than 2.5 cm at service load.

4 CONCLUSION

In present research a bridge abutment system consists of deep battered pile foundation with a nailed slope with flexible geogrid as the facing element is studied. In the numerical analyses, 2 different strategies were
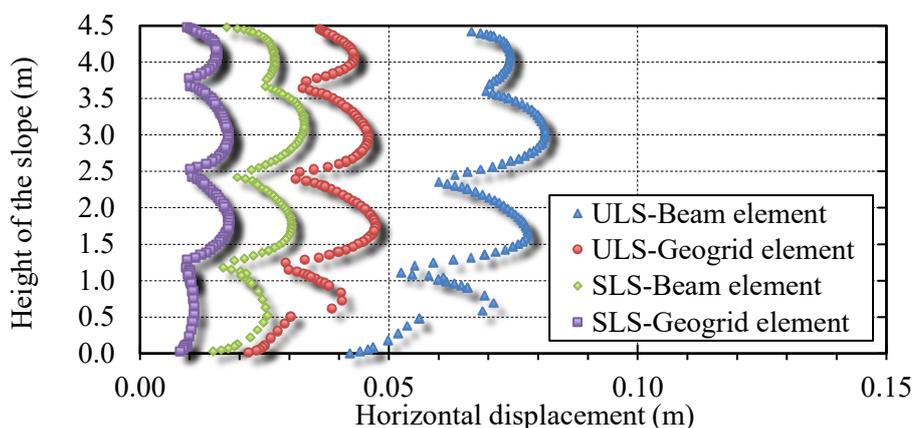
Figure 7. Horizontal displacement of the nailed surface

adopted that one accounted for the shear and bending resistance of the nails by modeling the nail as beam element. In the second approach, the nail was assumed to behave as an axial element with no bending and shear resistance and the nail was modeled by the use of geogrid element. Additionally, the behavior of the system in terms of the structural forces, mobilization of the shear strength on the domain and the deformation of the abutment face was examined at service and ultimate load states. Based on the numerical analyses conducted, the following conclusion can be drawn:

- Geosynthetic reinforcement with sufficient tensile strength and axial stiffness can be successfully used as the facing elements in the nailed slopes. The bending and shear resistance of the nail has a limited influence on the tensile force developed in the flexible geogrid facing.
- Considering the bending and shear resistance of the nails leads to an increase of about 10% in the numerically estimated tensile forces in the nail.
- The horizontal displacement of the abutment face at ultimate load state significantly differs when the nail is modeled as beam element.
- The shear forces at the connection between the piles head and the bank seat increases up to 100% when the nail is simulated as the beam while the distribution of the shear force in the pile length does not change significantly with type of the nail element.

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