Numerical modelling of a coastal embankment reinforced with geosyntethics

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ABSTRACT
Geosynthetics are widely used in civil, environmental, hydraulic and coastal engineering for slope stability control and coastal erosion prevention. In the harbours, coastal dikes are often equipped with geosynthetics for reinforcement purposes. Complex stress-strain interactions arise among the dyke materials, geosynthetics, wave actions and other external loads such as stored materials dredged up from the seabed. This paper investigates the behaviour of a geosynthetics reinforced coastal dike in the harbour of Gaeta in southern Italy. A detailed data-set is available for a dike recently extended by 314 m and reinforced through a geosynthetics mattress filled by concrete and equipped with draining points. Both limit equilibrium and stress-strain analyses are performed for the construction sequence. The achieved results show that the design of dyke and geosynthetics mattress requires advanced stress-strain analyses due to the complex geometry and loading sequence.

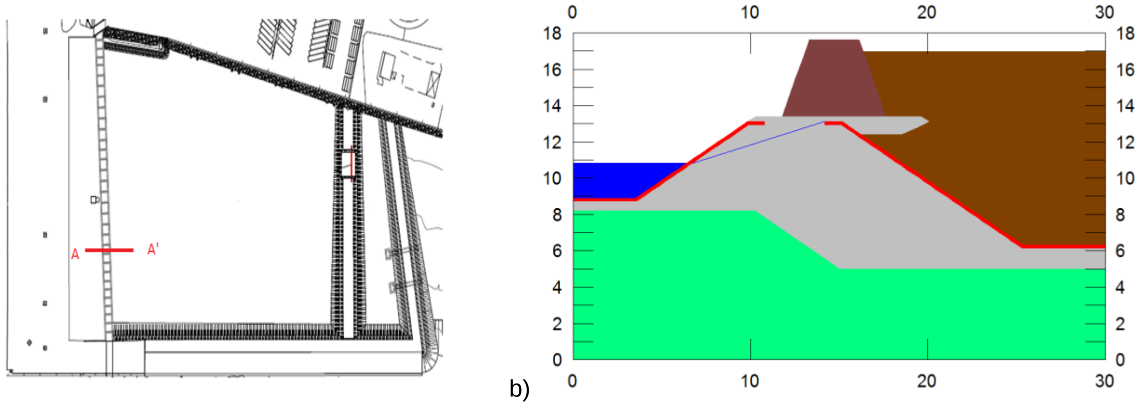
1. INTRODUCTION

Geosynthetics have been widely used in civil and environmental engineering for slope stability control (Cuomo et al., 2013) and in hydraulic and coastal engineering for coastal erosion prevention (Pilarczyk, 2000, 2003). Particularly, coastal dikes in harbours are often equipped with geosynthetics to either fasten the consolidation processes after construction or for reinforcement purposes against the waves' action in the long-term period. For this latter aim, both bags, geotubes, geocontainers can be efficiently used and the design of these structures is still based on black-box approaches and/or simplified limit equilibrium methods (LEM).
However, complex stress-strain and hydraulic interactions arise among the dyke materials (sand/gravel), geosynthetics (geotextile/mattress), wave actions and other external loads, especially when dykes are used to store materials dredged up from the seabed; thus, more advanced approaches should be tested for better evaluating the stress-strain behaviour of the geosynthetics cover during the construction and loading stages. Among the available numerical techniques, Finite Element Method allows assessing relative displacements and stress variations under the hypothesis of small deformations which is well suited if the structure is resistant and stiff enough. On the other hand, LEM coupled with FEM-derived information allows evaluating the approximations made in the standard LEM-based analysis.
This paper investigates the geosynthetics-based reinforcement of coastal dikes/embankments with special reference to the case of Gaeta harbour in southern Italy. Particularly, a detailed data-set is available for an existing dike recently extended by 314 m and reinforced against wave-induced erosion/failure through a geosynthetics mattress filled by concrete and equipped with draining points. Both limit equilibrium and stress-strain analyses are performed for the real construction and loading sequence and comparisons are provided among the results obtained with standard LEM analyses and more advanced FEM and LEM-FEM approaches.

2. CASE STUDY

Gaeta harbour is one of the most important infrastructures in the Southern part of Lazio region (Italy) and it is currently characterized by 900 m of dykes and 12,000 m^2 of platforms. This paper deals with the extension of a dyke – located at the Southern part of the harbour, near the Salvo D'Acquisto dyke - which followed a complex sequence of steps: i) extension of the dyke over 314 m through the construction of an embankment 5.2 m high, 2:3 steep with the foundations level located at -2.0 m (later named "principal embankment"); ii) dredging of seabed material from 0 to -10 m a.s.l.; iii) construction of a storage basin filled with 6÷11 meters of excavated materials and iv) raising of the dyke with a geosynthetics-reinforced embankment later named "secondary embankment"), v) filling of the additional storage volume (Fig. 1).
Particularly, two types of geosynthetics were used: i) a draining geocomposite called "Interdrain GMG 612" located at the bottom of the dredged material disposal to fasten pore water pressures dissipation, ii) a mattress called "Flexitex Filter Point" used to protect the flanks of the dyke, made of tout-venant, from erosion actions of sea waves. Particularly, the "Interdrain GMG 612" is a high-density polyethylene (HDPE) geonet with two Polypropylene (PP) geotextiles heat laminated. The geonet is made with 2 overcrossed strands at 60º, whose geometry creates channels with a high flow capacity, also under high normal stresses and at very low gradients. On the other hand, the "Flexitex" mattress is characterized by a 13÷30 cm thickness, draining points 0.2 m large and 0.5 m spaced, filled with light concrete and lined over the trapezoidal section of the embankment.
It is worth noting that the secondary embankment is 4 m high and it mainly aims to guarantee a larger storage volume; the external front is 70° steep, the base is 6 m large while the upper width is 2.83 m to allow mechanical

compaction of the embankment; however, the analysis of the behaviour of the secondary embankment is beyond the scope of this paper and it is assumed as an homogeneous material with high resistance and stiffness parameters.
After the final construction stage, the analysed dyke is subjected to the action of the average sea level on the left hand-side while the right hand-side bank undergoes a complex loading sequence, namely: i) sea wave actions after construction, ii) lateral pressure of the dredged materials located in the storage basin (up to 12 m a.s.l.), iii) self-weight of the secondary embankment, iv) self-weight of the additional stored volume (3.57 m high).
Aimed to understand the behaviour of the dyke, stress-strain FEM analyses are firstly carried out simulating the construction sequence; then, classical LEM approaches are used to compute the global factor of safety (FS) of the structure; finally, FS is evaluated through unconventional LEM-FEM coupled approach which refers to the stress field obtained by FEM analyses.



a) b)

Figure 1. a) Plainview and b) main section AA' of the reinforced dyke (modified from data received courtesy of Autorità Portuale di Civitavecchia).

3. NUMERICAL ANALYSES

3.1 Finite Element Method (FEM) analyses

Stress-strain FEM analyses are performed using a simple non-associated elastic perfectly plastic Druger-Prager constitutive model for all the materials of table 1. Particularly, the seabed material is constituted by silts and clays (# 1), the dyke is made of tout-venant (# 2), the Flexitex mattress is filled with concrete (# 3), the material excavated is sand (# 4), the secondary embankment is simply schematized with a high frictional-cohesion material (# 5). All the analyses refer to effective soil stresses and to the construction stages of tab. 2; the presence of a water table inside the dyke (from stage 3 onward) is simply taken into account considering the submerged soil weight, thus referring to hydrostatic pore water pressures which is nearly the case under study due to: i) small inclination of piezometric line, ii) almost impervious boundary imposed by the geosinthetics-concrete mattress. An unstructured mesh of triangles - not larger than 0.4 m inside/near the mattress and smaller than 2 m elsewhere - is used (Fig. 2a).

Table 1. Mechanical properties of materials.

ID	material	γ (KN/m^3)	γ_d (KN/m^3)	E(kPa)	ν	c (kPa)	φ (°)	ψ (°)
1	silts and clays	18	-	2 e4	0.25	5.75	25.5	0
2	tout-venant	20	18	7 e4	0.3	0	40	0
3	light concrete	25	-	2.7 e7	0.1	50	35	0
4	sands	17	-	3 e4	0.3	0	30	0
5	secondary embankment	20	18	7 e4	0.3	50	40	0

Table 2. Construction stages of the storage basin and filling with material dredged from seabed.

stage	description	external loading		piezometric line
		left	right	
1	self-weight seabed material	-	-	-
2	dyke construction	-	-	-
3	dyke under sea wave action		sea level - 0.6 m a.s.l.	0 m a.s.l.
4	storage at right-hand side		dreged material + 2.2 m a.s.l.	0 m a.s.l.
5	secondary embankment	sea level 0 m a.s.l.	dreged material + 2.2 m a.s.l.	inclined
6	storage at right-hand side		dreged material + 4.1 m a.s.l.	inclined
7	storage at right-hand side		dreged material + 5.8 m a.s.l.	inclined

Figure 2 shows the results achieved for dyke construction and later loading stages. It is worth noting that the high-stiffness of the “Flexitex” concrete mattress causes a stress concentration at the flanks of the embankment, in all the construction stages, thus reducing deformation and stress levels within the core of the dyke and in the seabed material. Consequently, small displacements are globally simulated (Fig. 3) whose values follow a complex spatial-time sequence due to the complex configuration of both geometry and stratigraphy. For instance, on left hand-side of the dyke, cumulated horizontal displacements increase from stage 2 to 5 and then reduce owing to the storage of an additional volume of dredged material (stage 6 and 7); on the right hand-side, horizontal displacements decrease with a similar time trend but smaller values. On the other hand, different spatial-time trends are simulated for the vertical displacements on left and right hand-sides.

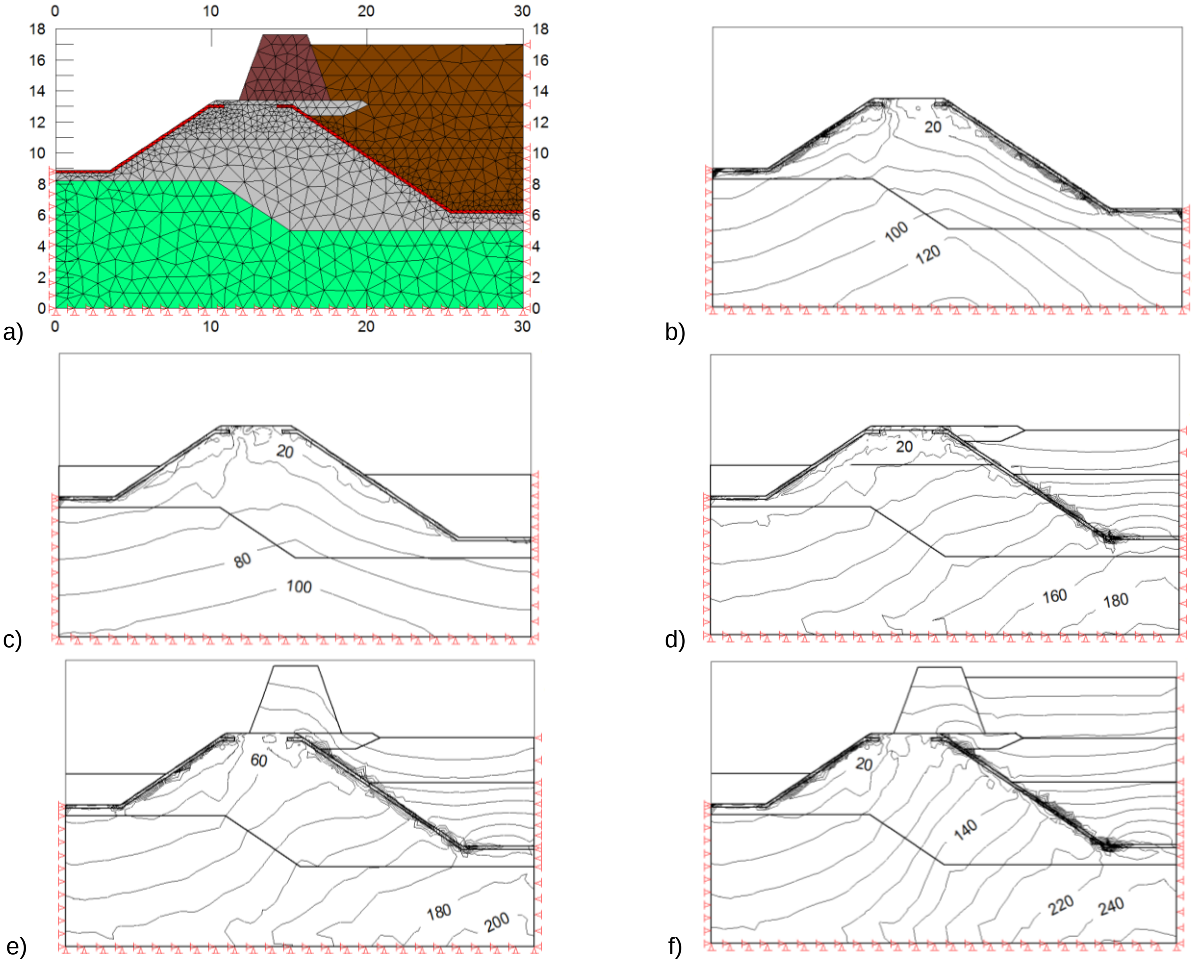


Figure 2. Unstructured FEM mesh (a) and effective vertical stresses during the construction stages: (b) stage 2, (c) stage 3, (d) stage 4, (e) stage 5, (f) stage 7.

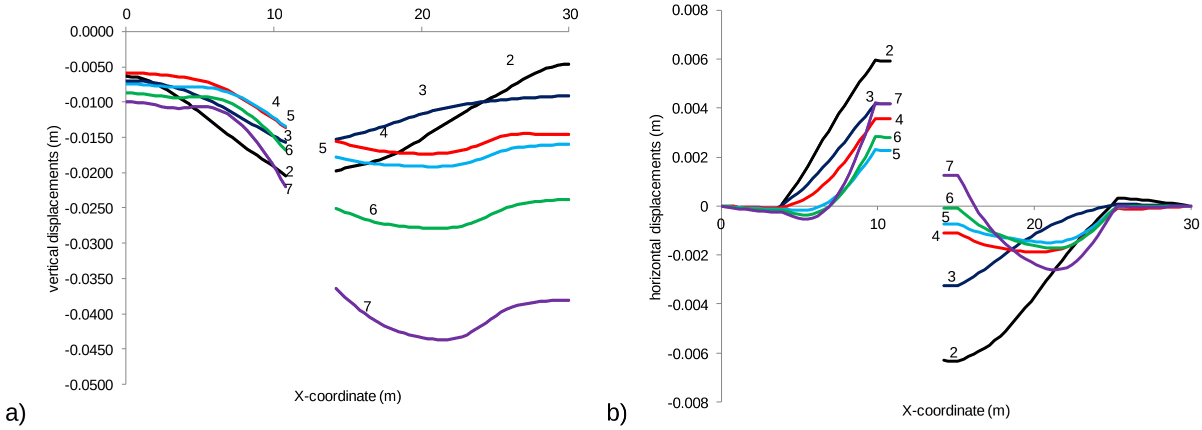


Figure 3. Simulated vertical (a) and horizontal (b) displacements (cumulated during the construction stages).

3.2 Limit Equilibrium Method (LEM) analyses

The standard Limit Equilibrium Methods of Janbu (1954) and Morgenstern and Price (1967) are used to evaluate the factor of safety (FS) of the dyke with reference to the construction stages of table 2.
Figure 4 shows the major slip surfaces of the dyke and the computed factors of safety (FS) which are strongly variable during the construction stages. Figure 4a-b highlights the importance of the hydraulic boundary conditions which determine a reduction of FS from 3.87 to 2.77 on the right hand-side, due to a low level of sea during wave action (up to a minimum of -0.6m). On the other hand, it is shown that simplified Limit Equilibrium Methods cannot give detailed information on slope stability if the external loads do not interact directly with the considered slip surface; this is the case of figure 4c-d which shows a constant factor of safety (FS) notwithstanding the filling of material on the right hand-side of the storage basin. Finally, figure 5 shows the shear stresses computed at the base of each slice of the considered slip surfaces (# 1 and # 2) which rely on the hypothesis that the ratio of mobilized shear stress to the shear strength is uniform along the slip surface. Particularly, where the slip surface intersects the external "Flexitex" concrete mattress, shear strength is quite high due to concrete self-weight and external loads; mobilized shear stress is related to FS rather than to the local strains of "Flexitex" mattress and surrounding soils if LEM is used.

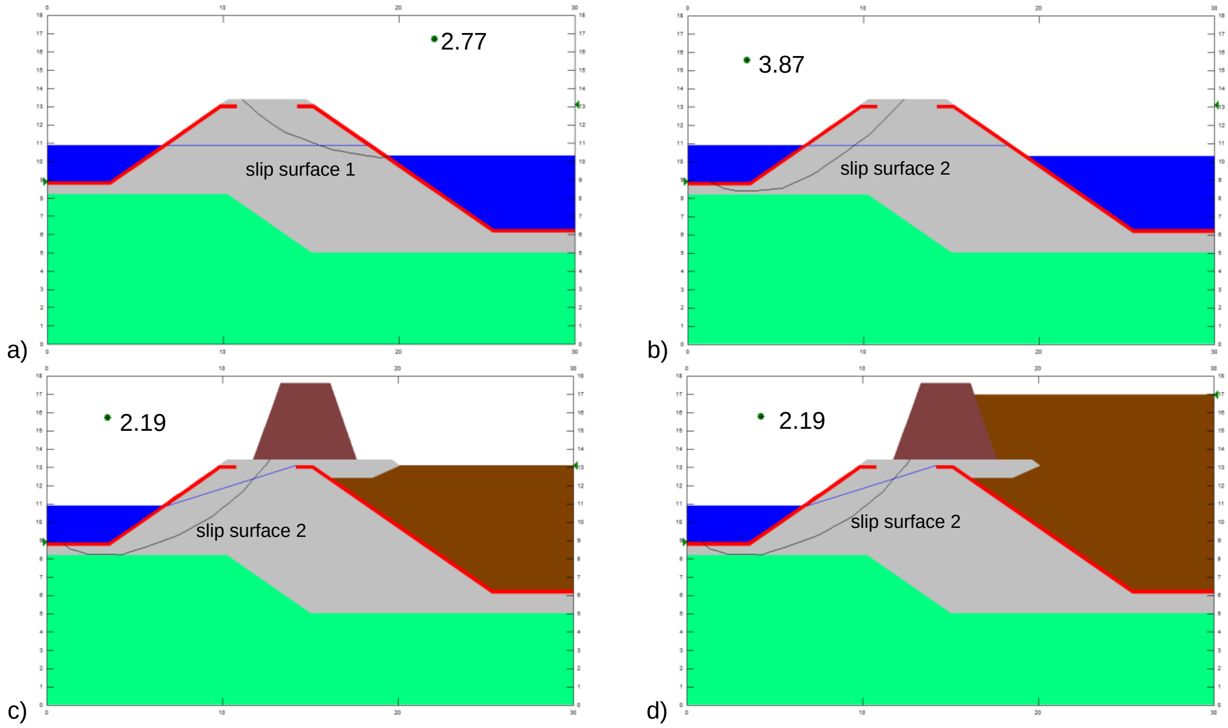


Figure 4. Slope stability conditions due to external loads: a) stage 3 (FS=2.77); b) stage 3 (FS=3.87); c) stage 5 (FS=2.19); d) stage 7 (FS=2.19).

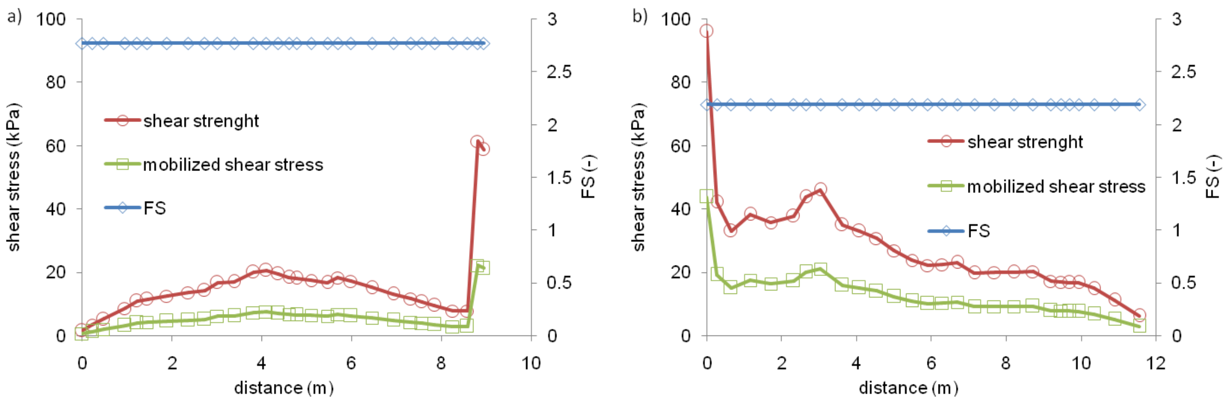


Figure 5. Shear strength and stress stresses mobilised at the base of each slices of the selected slip surfaces and Factor of Safety (FS) computed through standard LEM: a) stage 3, slip surface 1 and b) stage 5, slip surface 2.

3.3 LEM analyses coupled with FEM

The Limit Equilibrium Methods of Janbu (1954) and Morgenstern and Price (1967) are then applied referring to the stresses computed via FEM (sect. 3.3). The obtained results are plotted in figure 6 and are quite different to those of figure 5: i) the computed Factor of Safety (FS) is far to be constant along the slip surface; ii) in the zones near the “Flexitex” mattress, FS can be either quite high (fig. 6a) or close to unity (fig. 6b); iii) shear strength of the “Flexitex” mattress can be either well captured (fig. 6a) or underestimated (fig. 6b) by standard LEM analyses. These differences highlight the importance to use sophisticated methods for slope stability analysis and for testing the durability of the whole work and concrete structures. Indeed, figure 6b clearly outlines that - despite a medium FS equal to 2.19 - the “Flexitex” mattress may undergo high stress mobilization values and/or even local failure.
A full comparison between the results of LEM and LEM/FEM is proposed in figure 7 and tab. 3. For stage 3 and 4 the two methods provide similar results (fig. 7a); on the other hand, for the stage 5-7 LEM provides a constant factor of safety (FS=2.19) while LEM/FEM correctly indicates a variation of the slope safety factor due to the filling of the storage basin up to the secondary embankment level (fig. 7a). Finally, it is worth noting that the minimum FS is attained at the stage 2 and LEM slightly overestimate the FS value (fig. 7a).

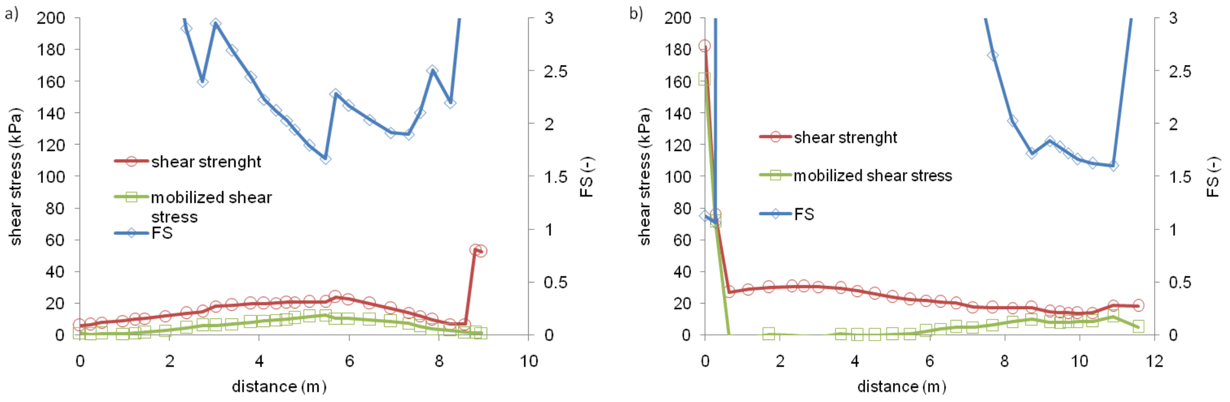
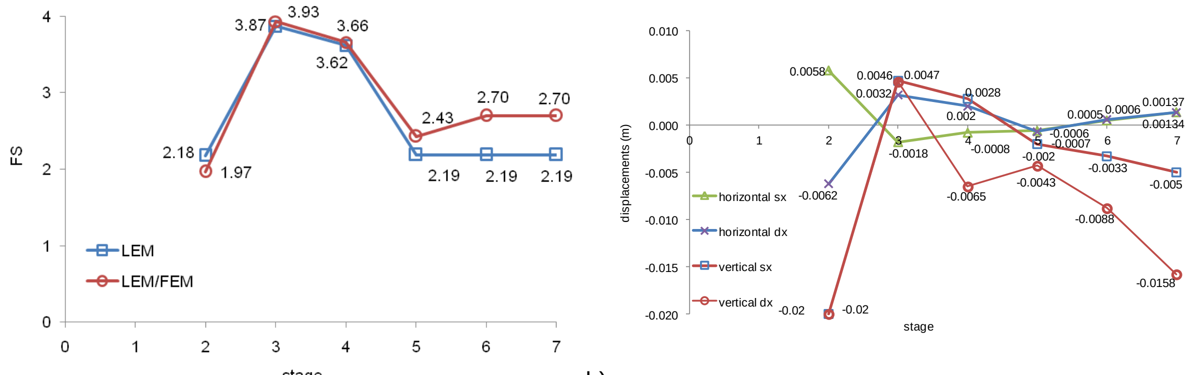


Figure 6. Shear strength and stress stresses mobilised at the base of each slices of selected slip surfaces and Factor of Safety (FS) computed through FEM/LEM analyses: a) stage 3, slip surface 1 and b) stage 5, slip surface 2.



a) b)

Figure 7. a) Comparison of the Factor of safety (FS) computed - for the slip surface #2 of fig. 4 - through standard LEMs and FEM/LEM analyses and b) X-Y displacements computed through FEM analysis.

Table 3. Comparison of the results of different methods (FEM, LEM, FEM/LEM).

Stage	FEM				LEM		LEM/FEM		Difference (%)	
	external load		x- dipl max (m)		FS		FS		LEM vs LEM/FEM	
	right side	left side	left side	right side	right side	left side	right side	left side	right side	left side
2	absent	absent	0.0058	-0.0062	-	2.18	-	1.97	-	9.6
3	-0.6 m a.s.l.	0 m a.s.l.	-0.0018	0.0032	2.77	3.87	2.99	3.93	7.4	1.5
4	+2.2 m a.s.l.	0 m a.s.l.	-0.0008	0.002	-	3.62	-	3.66	-	1.1
5	+2.2 m a.s.l.	0 m a.s.l.	-0.0006	-0.0007	-	2.19	-	2.43	-	9.9
6	+4.1 m a.s.l.	0 m a.s.l.	0.0005	0.0006	-	2.19	-	2.7	-	18.9
7	+5.8 m a.s.l.	0 m a.s.l.	0.00137	0.00134	-	2.19	-	2.7	-	18.9

Globally, LEM and LEM/FEM provide a maximum difference of FS equal to 18.9 % which could be acccepted only in a early stage design of this type of work. Particularly, figure 7b shows that the evolution of strain/diplacement fields inside the work during the cosntruction stages is direclty connected to the value of FS and the spatial-time variation of strain fields determines the amount of differences between the used methods.

4. CONCLUSIONS

Geosynthetics-reinforced slopes are widely used in civil and environmental engineering for highways and more recently also for coastal erosion prevention. The paper investigates a geosynthetics reinforced coastal dike in the harbour of Gaeta in southern Italy for which a detailed data-set is available. Both limit equilibrium and stress-strain analyses are performed for the real construction sequence of the structure. The achieved results show that the design of dyke and geosynthetics mattress requires advanced stress-strain analyses due to the complex geometry and loading sequence and the factor of safety can be even underestimated when standard limit equilibrium methods are used.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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