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The application of the Boolean Stochastic Generation Method to model seepage under levees in heterogenous soils

L'application de la methode de Génération Stochastique Booléenne pour modéliser des infiltrations sous des levées dans des sols hétérogènes

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ABSTRACT: Soil heterogeneity plays an important role in incrementing the uncertainty about the reliability of geotechnical engineering works, especially levees. The presence of thin layers of soils more permeable than the surrounding matrix significantly changes the seepage flow net below and within the dike. However, the detection of these layers is extremely difficult. Consequently, to evaluate the overall safety of dikes it may be useful to adopt stochastic computation methods.
The paper presents the calibration of a seepage model of an operational river embankment subject to sand boils. The levee, located along the Adige River (South Tyrol, Italy), has been monitored since 2016. Piezometers and spot temperature sensors are installed in the lateral banks while a distributed fiber optic sensors (FOS), buried in a 350 m long trench at the toe of the levee, is used to check temperature distribution in the subground.
The Boolean Stochastic Generation (BoSG) method addressess the influence of layers of material with different properties with respect of the surrounding soil. 360 soil configurations were generated for a two-dimensional groundwater flow model of the levee and confronted with the monitoring data of two piezometers. This analysis permits to identify the configuration that has effects more congruent with piezometers data, which in this case is a configuration with a major presence of lenses on the waterside respect the fieldside. This evidence could guide strategies for remedial works.

RÉSUMÉ:
L'hétérogénéité des sols joue un rôle important dans l'accroissement de l'incertitude quant à la fiabilité des travaux d'ingénierie géotechnique, en particulier les levées. La présence de fines couches du sol plus perméable que la matrice environnante change de manière significative le réseau d'écoulement des eaux d'infiltration au-dessous et à l'intérieur de la digue. Cependant, la détection de ces couches est extrêmement difficile. Par conséquent, pour évaluer la sécurité globale des digues, il peut être utile d'adopter des méthodes de calcul stochastiques.

Le document présente le calibrage d'un modèle d'infiltration d'un remblai de rivière opérationnel soumis à des volcans de sables. La levée, située le long de la rivière Adige (Sud deTyrol, Italie), est contrôlée depuis 2016. Des piézomètres et des capteurs de température ponctuelle sont installés dans les berges latérales, tandis qu'un capteur à fibres optiques distribuées (FOS), enfouis dans une tranchée longue de 350 m au pied de la digue, est utilisé pour vérifier la répartition de la température dans le sous-sol.
La méthode de génération stochastique booléenne (BoSG) prend en compte l’influence des couches de matériau ayant différentes propriétés par rapport au sol environnant. 360 configurations du sol ont été générées pour un modèle bidimensionnel d'écoulement des eaux souterraines de la digue et confrontées avec les données de monitorage de deux piézomètres. Cette analyse permet d’identifier la configuration ayant des effets plus congruent avec les données des piézomètres, qui dans ce cas, est une configuration avec une présence majeure de lentilles au bord de l'eau par rapport au terrain. Cette preuve pourrait orienter les stratégies pour les travaux de réparation.

Keywords: Levee, seepage model, sand boiling, soil heteroigenity, stochastic model.

1 INTRODUCTION

Marked soil heterogeneity is an important source of uncertainty for geotechnical engineering works (Kulhawy 1992; Whitman 2000). Knowing the location and distribution of thin, small levels of soils within a uniform soil matrix may seem for most of practical applications useless (Vick 2002). In fact, in general, when in the stratigrapy thin layers of soils that do not match the surrounding material are found, they are usually discarded (Kulhawy & Phoon 1996). The assumpition is that their dimensions, so little with respect of the geometry of the investigated problem, would not affect the overall dynamic of the process

However, this is not the case for stability problems when the rehological parameters are markedly different (Bossi et al. 2016; Bossi & Marcato 2016; Wang et al. 2018; Hicks & Li 2018). Even more, seepage-related geotechnical problems are extremely sensitive to the local variations of soil permeability (Yang et al. 2018). Small levels of soils more permeable than the surrounding matrix change significantly the seepage flow net below and within levees or other earth-made object (Wen & Gómez-Hernández 1996). Nevertheless, most of the times the investigation procedures, wheareas indirect such as geophysical surveys or direct such as boring, do not allow to detect and precisely extimate the extent of these layers (Niederleithinger et al. 2012; Rings et al. 2008).

Therefore, in this paper the use of a stochastic technique is proposed to evaluate the effect of the presence of scattered and more permeable thin soil levels below a dike.

2 THE BOOLEAN STOCHASTIC GENERATION METHOD

The Boolean Stochastic Generation method (BoSG) is an algorithm that allows to randomly generate lenses of material with specific properties within a defined geometry. The method is called Boolean since the material is either *matrix* (the greatest part of what is found in that stratigraphic level) or *layer* (inclusions or thin levels of material with different soil properties). Boolean methods have been both used for modelling petroleum reservoirs (Dubrule 1989) and fluvial facies (Mackey & Bridge 1992; Deutsch & Tran 2002). In fact, fluvial deposits, expecially in the context of meandering rivers, are characterized by alternation of soils of different grain size and permeability linked to the natural geomorphological migration of the channel belt in the floodplain.

In levees, using a stochastic model that may account for the presence of more permeable layers within the foundation or the body may be useful for the assessment of seepage-related reliability.

2.1 The BoSG algorithm

The algorithm has been developed in FLAC and FLAC3D, finite difference numerical codes for geotechinical modelling, but the approach may be implemented within many other numerical models.

The algorithm follows four steps:

1. Mesh geometry definition: specific properties and rehologies are assigned to the materials of the investigated problem;
2. Layer generation: a MatLab$^{(R)}$ script reads the mesh geometry and generates n different distribution of layers. The location of the layer center is randomly selected from an uniform distribution, while the lenght and, in 3D problems, the width of the lens are selected through a normal distribution compatible with the geo-morphological process that generated the soil layering. Then a text file readable by FLAC/FLAC3D is produced with all the n-generated soil configurations;
3. For seepage analysis: FLAC/FLAC3D computes the text file and calculates automatically all the n possible solutions. In general the number of the possible analysed configuration is selected in function of the computational time available for performing the stochastic analysis;
4. Reliability evaluation of results: anotherMatLab(R) script automatically analyses the pool of results comparing them to the reference data and calculating the reliability parameters in order to select the most reliable configuration;

All the results remain available to be handled with FLAC/FLAC3D. In this work, the BoSG method has been apllied in a bi-dimentional environment.

3 THE TEST SITE

The test site is located near Salorno in the Province of Bolzano, in North East Italy (46°14′11.0″N 11°10′52.8″E). It consists of a 350 m long portion of the right earth levee of Adige river. It is 4 to 4.5 high with a 1.5 m high berm on the landside (Figure 1). In addition to the small town of Salorno, very close to the area there are the highway and the railroad that lead to Austria,

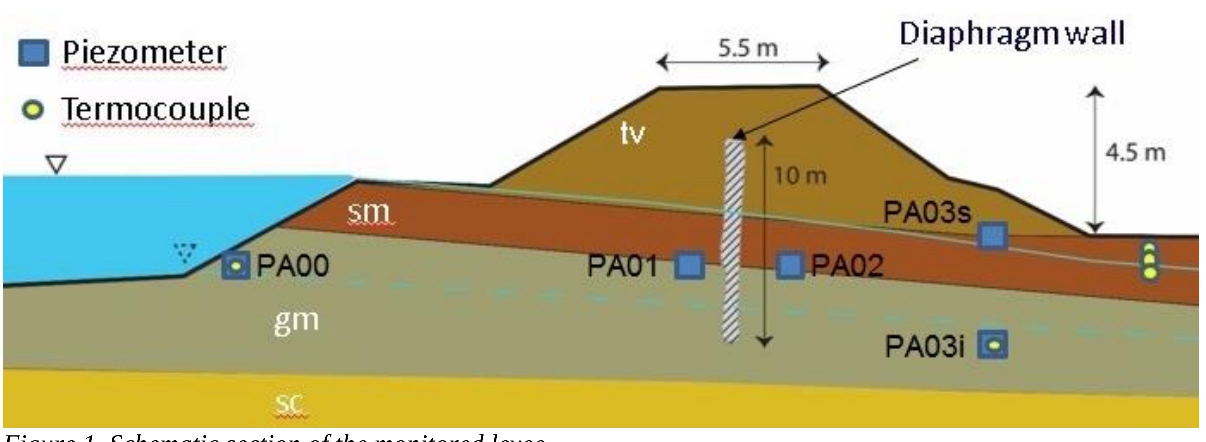

Figure 1. Schematic section of the monitored levee

so the risk linked to a possible collapse of the dike is high due to the abundance of exposed elements.

In past times, the river was free to migrate along the narrow alluvial plan. Therefore, a complex sedimentological environment with point-bar structures and paleo-channels characterizes the subsoil system.

Several anthropic interventions were performed in the area to protect the human settlements, and in the 19th century, straight embankments were realized to confine the river and find space for the modern communication routes.

Since its construction the new straight levee has be always subject to sand boiling during the floods, inducing the administrators to intensify the attention on it and make some intervention to mitigate the probelms induced by internal erosion. Some works were performed in 1998, when the levee was ameliorated with a 10 m deep jet-grouting seepage cut-off diaphragm (Figure 1).

3.1 *Investigation and monitoring*

Seven boreholes allowed to delineate the general stratigraphy of the levee. The dike body is composed by a heterogeneous man-made soil (tv). The natural soil profile may be shematized with a superficial layer of silty sand (sm) lying above a thick layer of sandy gravel (gm); a clayey sand (sc) may be find below all (Figure 1).

Along, five Lefranc tests (EN ISO 22282-2/2008) were performed to evaluate the permeability of the different strata. Results are shown in Table 1.

Geophysical surveys performed with Electrical Resistivity Tomography (ERT) shown that the stratigraphy of the area is highly heterogeneus. More resistive levels of coarser material are detectable and interpretable as paleo-channel deposits (Bossi et al. 2019), representing coarser sandy and gravel levels. These results are compatible with the old Austrian cartographical evidence (Scorpio et al. 2018) that show a meander, eliminated with the construction of the investigated levee.

At the moment two dike sections are monitored with piezometers and termocouples working in quasi-real-time. Particularly, in section A, schetched in Figure 1, a Casagrande piezometer was placed on the riverside to measure the river water level (PA00). Other two

Table 1. Values derived from the Lefranc tests

Soil	k [m/s]
Tout-venant (tv)	9.70E-07
Silty sand (sm)	9.77E-06
Sandy gravel (gm)	2.10E-05
Clayey sand (sc)	6.29E-06

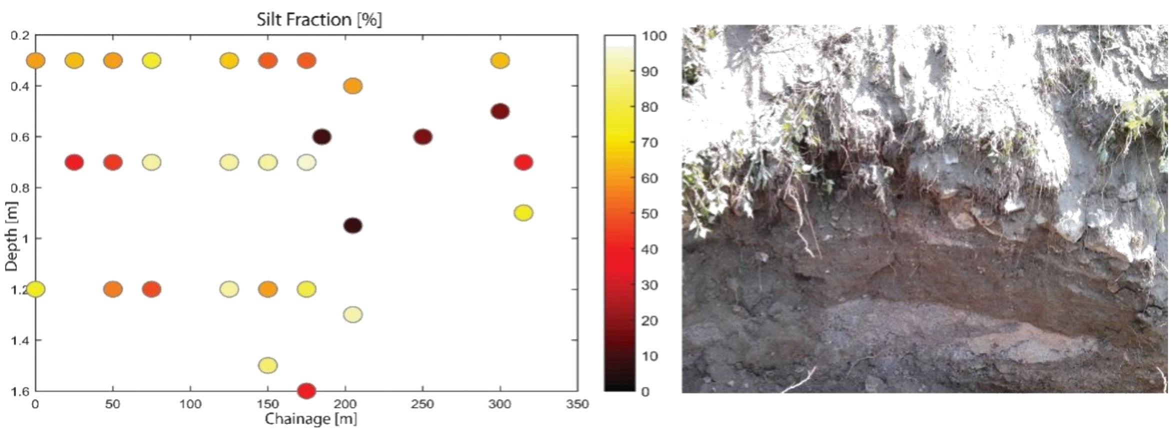

Figure 2. Location and silt fraction of the samples collected in the trench (a); detail of a lens (b)

piezometers were installed on both sides of the jet-grouting wall to assess its effectiveness (PA01 and PA02), while other two piezometers were placed at different levels below the berm (PA03s and PA03i).

Besides, a distributed fiber optic sensor for the temperature monitoring (Bossi et al. 2018) was installed in a 1.6 m deep trench excavated on the landside at the toe of the levee.

During the excavation 30 samples were collected from the trench sides and subject to grain-size analysis to evaluate their composition. Results from the analysis show that the material found in the trench it is extremely heterogenous with markedly different grain size also in samples that are located very near from one another (Figure 2). Particularly, some lens of sandy soil, with some gravel grains and cobbles inside, are occasionally observed during excavation, as clearly evidenced by the photo reported in Figure 2*b*.

In this case using modelling techniques that assume a normal distribution of soil properties within the layers to proceed with a stochastic analysis may induce only additional errors.

4 MODELLING APPROACH

The capability of BoSG modelling to reconstruct and provide insight on the dynamic of seepage process under levees was tested on this case-study. The model was calibrated using a moderate flood event recorded in June 16th and 17th 2016, because in the monitored period no intense flood was observed.

4.1 Geometry and loads

The 2D seepage models were built based on the geometry of section.

The mesh is composed by quadrilater elements of almost equal thikness: 0.20 m thick elements in the most superficial layers , 0.40 m for the lowest strata.

The properties of soils were assigned according with the results of the geotechnical investigation. The diaphragm was considered as a homogeneous and impervious material.

Hydraulic load variations corresponding to those observed at the PA00 piezometer during the recorded flood event are imposed on the riverside. On the landside, sufficiently far from the levee, the undisturbed water table is set to be 1.80 m below ground surface.

4.2 BoSG parameters and model calibration

The BoSG analysis was performed randomly generating lensens and assuming they were constituted by material with different permeability. The lenses were generated only in the *sm* and *gm* strata since it was supposed that the process inducing the formation of sand boils develops in those superficial levels.

The thickness of lenses was 20 cm in all the analysis, but their number and lenght was varied according with the stochastic geometry generation developed inside the algorithm (step 2). Particularly, 30 possible configurations of generated lens were investigated, assumung a fixed number of lens equal to 3, 6, 9 and 12 respectively, for a total of 120 simulations.

Moreover, the analysis were repeated assuming a permeability of lenses respectively equal to 3 times (Condition A), 6 times (Condition B) or 10 times (Condition C) the *gm* permeability (Table 2). In this way, the total number of performed simulation reached 360.

5 RESULTS AND DISCUSSION

The reliability of analysis was based on the data of piezometers PA03 and PA04i. The pool of all 360 simulation was automatically analyzed.

The simulations were scrutinized through the evaluation of a congruence index (CI) measuring the discrepancy between the modelled and the recorded data. The congruence index was defined as the sommatory of the absolute difference between the pressure head measured at the piezometer and the modelled one in the same

Table 2. Permeability values of lenses

Condition	k [m/s]
a	6.29E-05
b	1.25E-04
c	2.10E-04

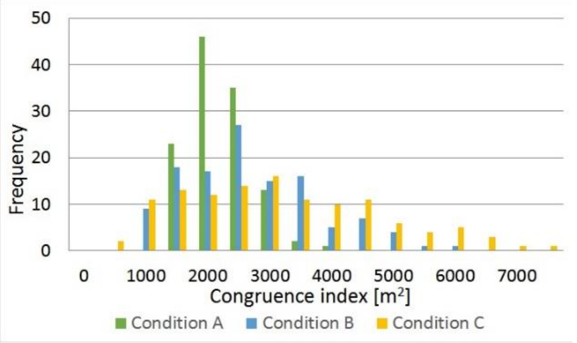

Figure 3. Distribution of the congruency index for all the simulations in function of lens permeability.

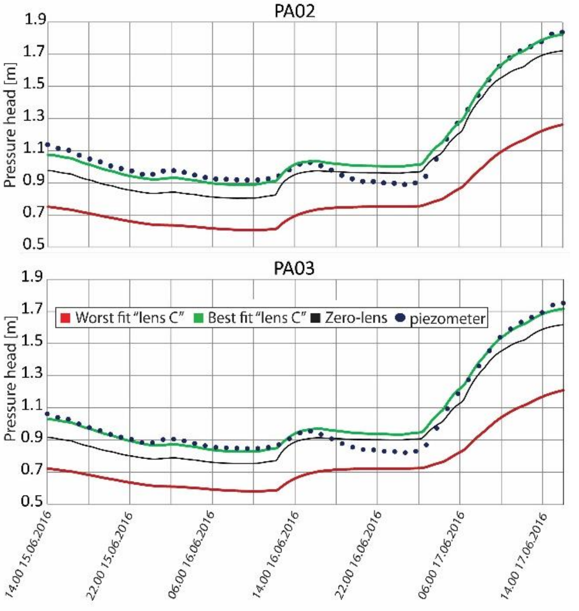

Figure 4. Pressure head at PA02 and PA03i obtained with the best and worst fitting models compared with measured data.

instance, with the sommatory extended for all the time steps of the simulated flood event. Small CI should indicate a good overlapping of the measured and modelled curves.

What came to evidence (Figure 3) is that on average the lowest CI was somewhat lower using the C condition, that is when the permeability of the lenses is higher. On the other side the standard deviation for Condition C is larger than for Condition A and B. In fact, also the highest CI values are obtained with Condition C.

The fact that the configuration with minimum CI have lenses with higher permeability means that it is likely that the layers that are present in the levee subsoil are constituted by a coarser material, and this is congruent with the geophysical investigation. But how much coarser? It is important to note that the difference in permeability is just of one order of magnitude and the soil may be still classified as sand by the permeability point of view. Thus the presence of a small amount of thin layers of soil with slightly higher permeability may change significantly the seepage dynamic of the investigated object.

In Figure 4 are depicted the results of simulations which offer the best-fit and the worst-fit with respect of the pressure head measured in PA02 and PA03i. They are compared with the reference data and with the trends obtained in absence of lens. First of all, it is importan to note that the difference is only imputable to the distribution of lenses since in both the simulations there were 12 lenses with the same permeability. Secondly, the variability induced by the presence of 20 cm thick lenses is very high, as the maximum difference between two models in pressure head reaches 50 cm at the peak. This confirmed the importance of heterogeneity in evaluating the overall reliability of a dike.

The CI of the zero-lens model (also reported in Figure 4) is at the 95th position among the 360 BoSG ones. The zero-lens curves falls for most of the analyzed event below the data recorded in PA02 and PA03i, with a maximum vertical error of 0.18 m. The error is small but not negligeble, even more considering that it provides results that are non-conservative.

Besides, results show that the best fit configuration has more lenses on the riverside while the worst fit has more lenses on the landside (Figure 5) and that induces the increase of preassure head on the landside (Figure 6). This is a recurrent pattern for the other configurations with lower or higher CI and it is congruent with the geophysical analysis that called for point bars remnants below the levee and on the riverside and for more silty material on the landside (Bossi et al. 2019). That means that the model configuration, selected only on the base of the piezometric data, supports and is in accordance with the indipendendent geophysical investigation, strengthening both the results.

6 CONCLUSIONS

Soil heterogeneity plays a central role in the seepage dynamic, and therefore for the overall stability, of levees.
The results of the BoSG analysis show that the presence of shallow layers (20 cm) with a permeability increased of just one order of magnitude influence significantly the seepage process below the levee. Discarding the possible presence of thin, more pervious layers may induce large errors in the seepage and stability analysis and threaten the overall reliability of the structure. Those layers are extremely common in alluvial plans, expecially in former meandering river that have been subject to anthropic rectification.

For our case-study the best fit configuration selected among the pool of the BoSG realizations is in accordance with the results of a geophysical investigation that calls for the presence of point bars remnants below the levee and on the riverside, and for more silty material on the near landside, between the levee and a paleochannel.

Further analysis will assess the errors associated with the hypothesis that the diaphragm is impervious. Since the waterproof cut-off wall has been constructed with jet grounting, it is possible that, when crossing more permeable layers, the soil pores would have not been completely filled by the injected grout, thus producing a pervious soilcrete. The BoSG method can help assess the variability of the results associated with the presence of discontinuity in the diaphragm induced by the presence of more permeable layers. The assessment of possible errors may guide the desing of both a secondary investigation

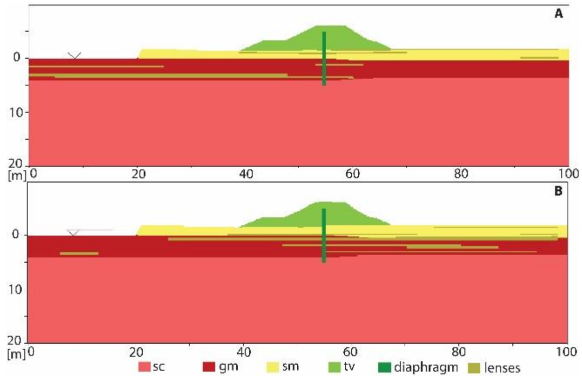

Figure 5. Lens location for (a) the best-fitting configuration and (b) the worst-fitting configuration obtained with condition C.

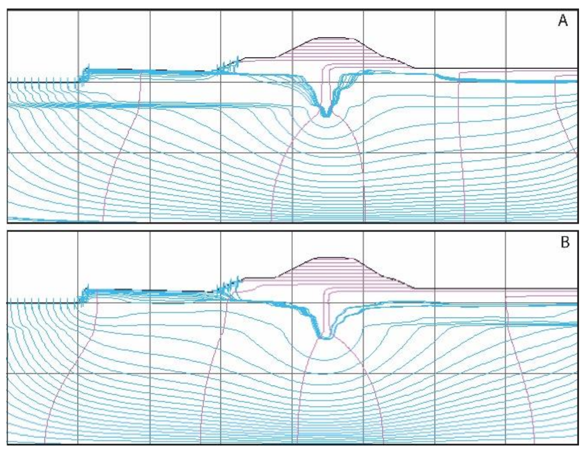

Figure 6. Flow net for (a) the best-fitting configuration and (b) the worst-fitting configuration obtained with condition C.

campaign and further structural countermeasure works.

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