# Seismic Analysis of Reinforced – Earth Wall on Precarious Soil Improved with Stone Columns

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ABSTRACT: The seismic response of a 15 m high reinforced-earth retaining wall on top of a soil deposit containing liquefiable soil layers is explored with effective-stress dynamic time history analyses. The simultaneous generation and dissipation of seismic excess pore-water pressures (EPWP) is reproduced in the analysis. The need for, and effectiveness of, soil improvement with 60 cm stone columns placed in a triangular configuration is demonstrated with a series of graphs. Improvement results from both the increased rate of EPWP dissipation and, mainly, the increased stiffness/strength of the system.

## 1 INTRODUCTION: THE MAJOR PROJECT

A significant project is heading to the final stage of planning — architectural, static, geotechnical, hydraulic and electromechanical: the Cultural Center of Stavros Niarchos Foundation located in the Athens coastal, covering approximately 200,000 square meters. The cultural center will include two interconnected buildings, the "National Opera" and the "National Library", and a theme park of grand expanse. The park will be developed on a manmade hill (landfill) of mild slope which culminated in an almost vertical edge 15m high, a small distance from the Library. Figure 1 shows a section of the hill, its vertical edge and the Library. Being the conception of the famous architect Renzo Piano (the architect of the Kansai airport terminal), the entire center and its facilities is planned to be in excellent harmony with the upgraded environmental surroundings and will consist a model of energy efficiency and economy in the use of water resources. The seismic design of the structural components of the project, including seismic isolation systems, is of equal importance from an engineer's point of view.

The stability of the practically vertical slope was one of the most interesting and challenging geotechnical issues, not only due to its significant height (15m), but also due to the precarious foundation soil, which comprises silty sand layers loose enough to be considered liquefiable. Moreover, because of the close proximity of the retaining wall to the library through an exit zone only 10m wide, the seismic motion for the design of the wall was chosen to be sufficiently high corresponding to a return period of 1000 - 2000 years — as in the case of the two buildings (Library and Opera).

The lack of space also led to the solution of an reinforced - earth retaining wall for the support of the vertical verge of the park hill. The current paper sheds light to the major findings regarding the seismic stability and the deformation of landfill − retaining wall− soil system, through dynamic effective stress analyses.

## 2 NUMERICAL MODELING

### 2.1 *Two-dimensional modelling of stone columns*

In the framework of the present study, the numerical simulation of the stone columns was performed assuming plane strain conditions. Several methods have been developed in the literature to convert the axismmetric unit cell to the equivalent plane strain model in terms of drainage (permeability) and bearing capacity (column stiffness). The method that was followed in this study has been proposed by Indraratna and Redana (1997) and validated by Tan, Tjahyon and Oo (2008).

According to this method, the total cross-sectional area of one column and its surrounding soil are preserved in both axisymmetric and plane strain conditions. The plane-strain column width can be estimated based on the equivalence of area replacement ratio. Given that the replacement ratios and the elastic moduli of soil are equal for axisymmetric and plane strain conditions ($a_{s,plane} = a_{s,axis}$ and $E_{s,plane} = E_{s,axis}$), the plane strain column stiffness is the same with the axisymmetric one ($E_{c,plane} = E_{c,axis}$). The plane strain soil permeability is taken equal to its axisymmetric counterpart, i.e., $k_{h,plane} = k_{h,axis}$ and $k_{v,plane} = k_{v,axis}$. This method thus retains the axisymmetric material properties for the plane strain geometry.

The validity of these approximations has been tested in two stages by Tan, Tjahyon and Oo (2008): comparison of unit-cell simulations and comparison with the field data from an embankment case history. It was shown that they reproduce well the 3D behaviour of stone columns.

### 2.2 *Dynamic numerical analysis*

The goal of this study is to investigate the behavior of the earth retaining wall under seismic conditions *with* and *without* stone columns. The actual stone column configuration in the field close to the Library consists of a triangular grid of stone columns with diameter 0.60 m and spacing 2 m, covering a width of 16 m under and slightly beyond the wall (see Figure 2a). The spacing of 2 m was preserved in the numerical simulation. Thus, for spacing of 2 m and radius equal to 0.30 m, the equivalent width of the stone columns in the plane strain model was estimated 0.14 m.

In total, two categories of dynamic analyses in terms of effective stresses were conducted, using the finite difference code FLAC (Itasca, 2005):

- with stone columns
- without stone columns.

In particular, Figure 2a illustrates the soil profile including the stone columns, with the assigned values of permeability and an indicative point where the excess pore pressure is recorded during the dynamic analysis. All the recording points were kept the same for the analyses without the stone columns in order to directly compare the results from the two categories of analyses. The seismic input motion applied at the base of the models is shown in Figure 2b. The simulation involves the constitutive law of Byrne (1991) for pore pressure generation which is incorporated in the standard Mohr-Coulomb plasticity model.

## 3 BEHAVIOUR OF EARTH WALL *WITH* AND *WITHOUT* STONE COLUMNS

In both cases (with and without stone columns), the deformation pattern of the soil–wall system is similar, but the displacements are considerably larger if no stone columns are installed. The displacement vectors in Figures 3b and 3c indicate the outward rigid-body movement and rotation around the toe of the wall of the reinforced part of the fill (which was modeled to behave elastically). This is accompanied by large displacements deep in the soil under the wall, tending to form an almost circular failure mode. In particular, the maximum horizontal wall displacement at the top is 23 cm with stone columns and 37 cm without stone columns (Figure 3a).

The distribution in space and time of excess pore water pressures (EPWP) is portrayed in Figures 4 to 6. It is evident that the medium sand exhibits a quite similar response in both cases (*with* and *without* stone columns). The excess pore pressures are dissipated at the same rate within the "critical" zone (below the earth wall), thanks to seepage of pore water towards the toe of the wall, which occurs regardless of the presence or not of stone columns (Figures 4a and 4c). This flow path towards the toe of the wall stems from the difference of the overburden stress and consequently of the excess pore pressure developing in the free field (no fill on top) as opposed to the soil below the fill. Thus the water pressures developing below the landfill are much higher than those in the free field. This difference which is very profound at the boundary of the wall, results in the above described water flow (from high pressures to lower ones).

Away from the "critical" area, the silty sand experiences more or less the same response in terms of EPWP generation. However, the dissipation of EPWP is understandably more profound with stone columns (Figures 4a and 6). This offers a rather clear evidence of a beneficial role of the stone columns. In addition, the increased stiffness of the foundation soil due to the presence of stone columns reduces significantly the outward movement of the earth retaining wall.

## 4. CONCLUSIONS

Improvement of the ground underneath the reinforced-earth wall forming the terminal boundary of the hill, was necessitated from the large height of the wall (up to 15 m) and the presence of soft and / or liquefiable soils in the supporting ground. “Stone-columns” have emerged as the likely choice to provide increased stiffness/strength in the foundation and help in rapidly dissipating “deleterious” seismic excess pore-water pressures. The scope of the numerical study is to assess the effectiveness of a particular stone column configuration in achieving these two objectives.

To this end, a numerical 2-dimensionsal (2D) seismic response analysis is performed in terms of effective stresses. To overcome the serious limitation of plane-strain modeling for the truly 3D geometry of the stone columns, an approximate equivalence of the axisymmetric flow of a single *circular* stone column with the 2D lateral flow of a single *row* stone column was enforced, along with stiffness compatibility.

The main conclusion of our study is that thanks to the relatively high permeability of the dense sand, medium sand and silty sand layers, dissipation of excess pore-water pressures developing during shaking is substantial. The presence of stone columns under the wall increases somewhat the rate of dissipation; but, moreover, it leads to increased robustness and thereby significant improvement of computed wall performance.

## 5. REFERENCES

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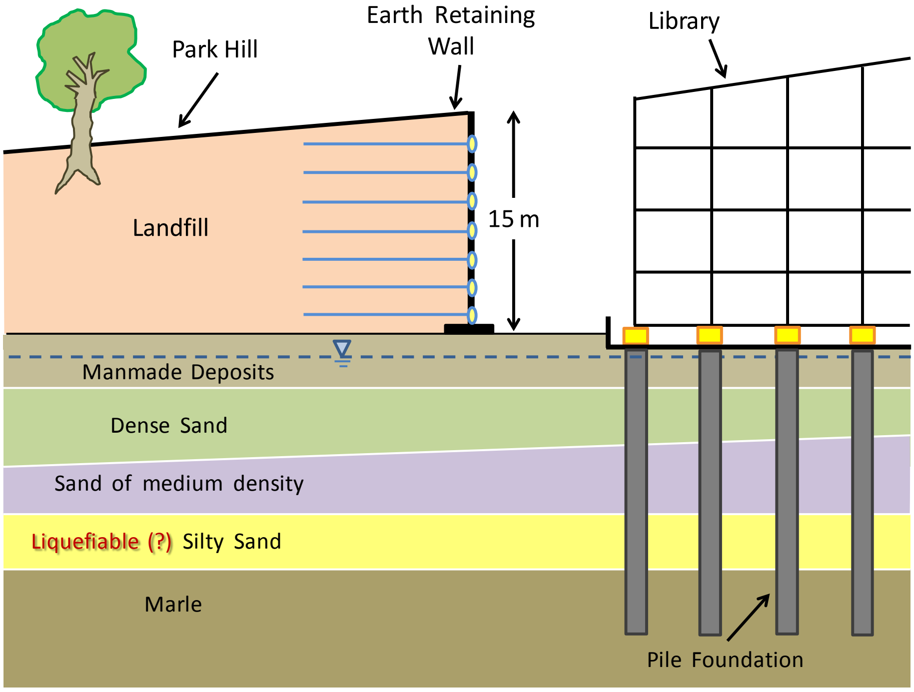

Figure 1. Sketch of the section of the retaining wall at the proximity with the Library.

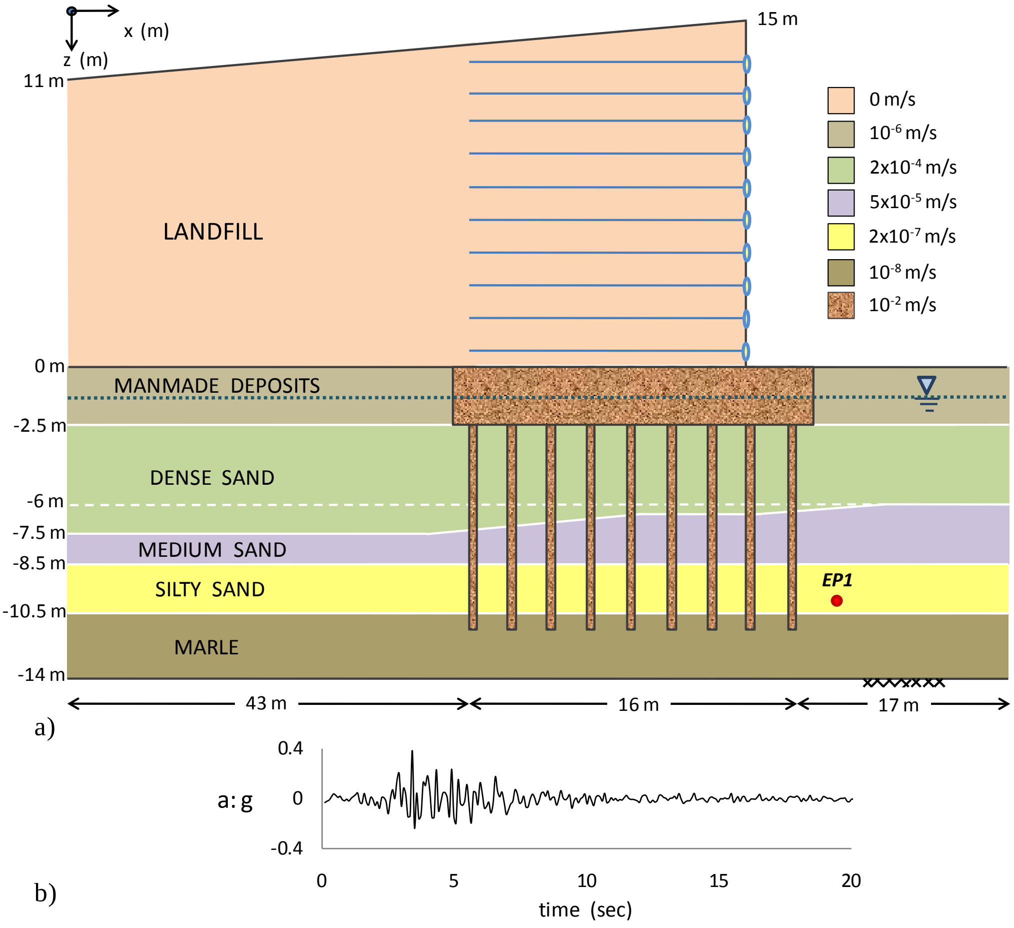

Figure 2. a) Illustration of the soil profile *with* stone columns and the permeability values assigned to the soils layers (left side); b) Input motion at the base of the models (Gilroy record, Loma Prieta Eq., 1989).

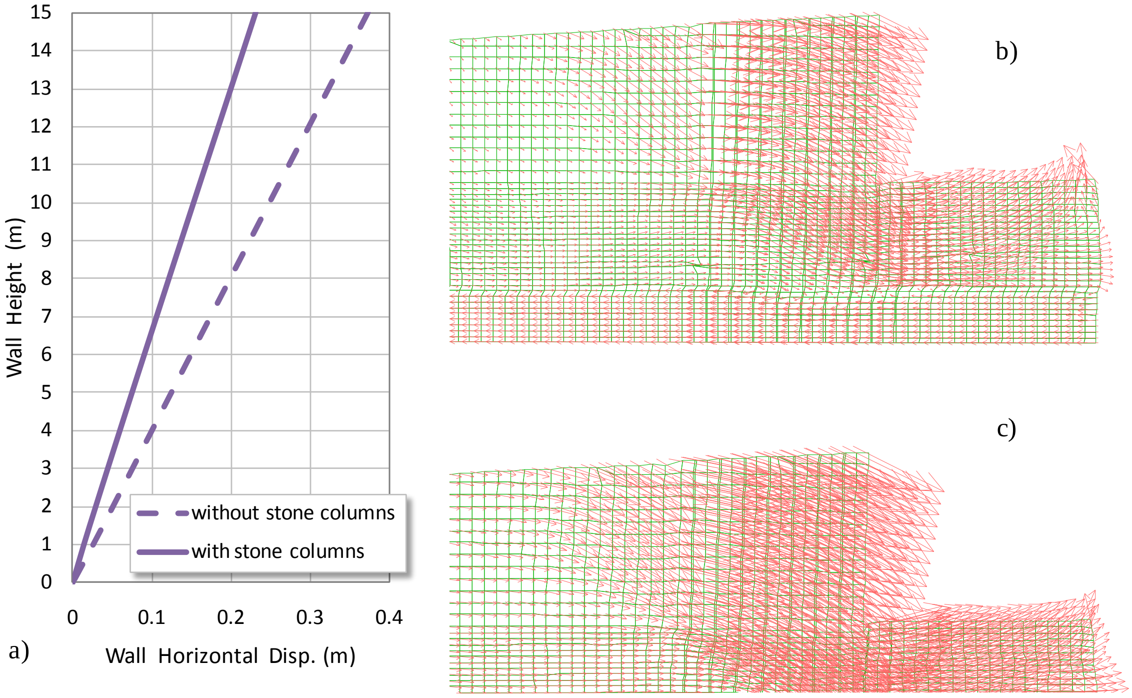

Figure 3. a) Distribution of horizontal displacements of the wall at the end of shaking, *with* and *without* stone columns; (b) Displacement vectors at the end of shaking, *with* stone columns; (c) Displacement vectors at the end of shaking, *without* stone columns.

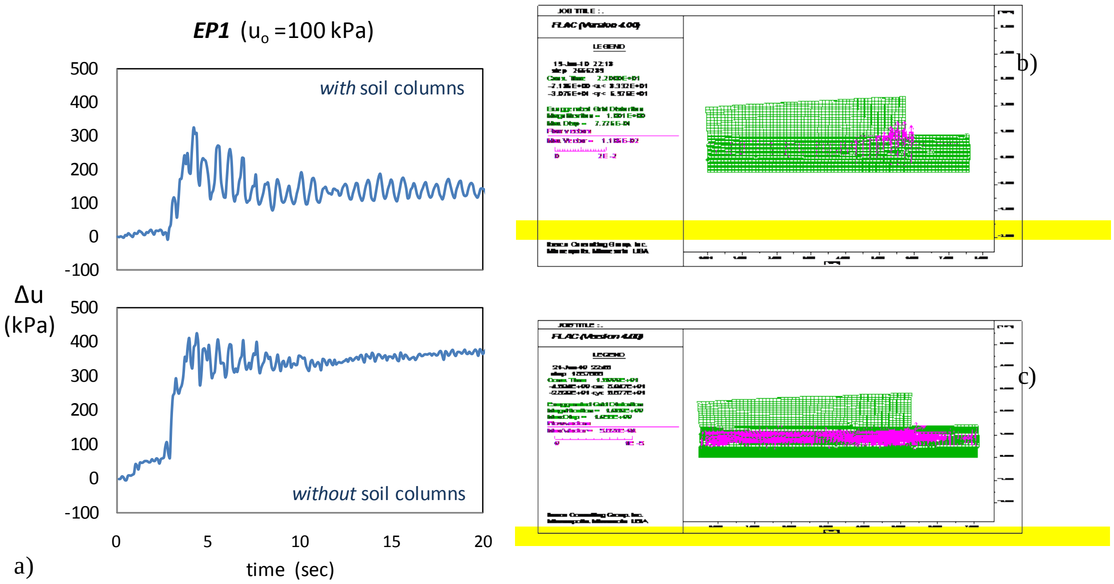

Figure 4. a) Time histories of excess pore-water pressures at a selected point within the silty sand layer (Figure 2) *with* stone columns (above) and *without* stone columns (below); b) Flow vectors during shaking *with* stone columns; c) Flow vectors during shaking *without* stone columns The silty sand layer has been colored yellow.

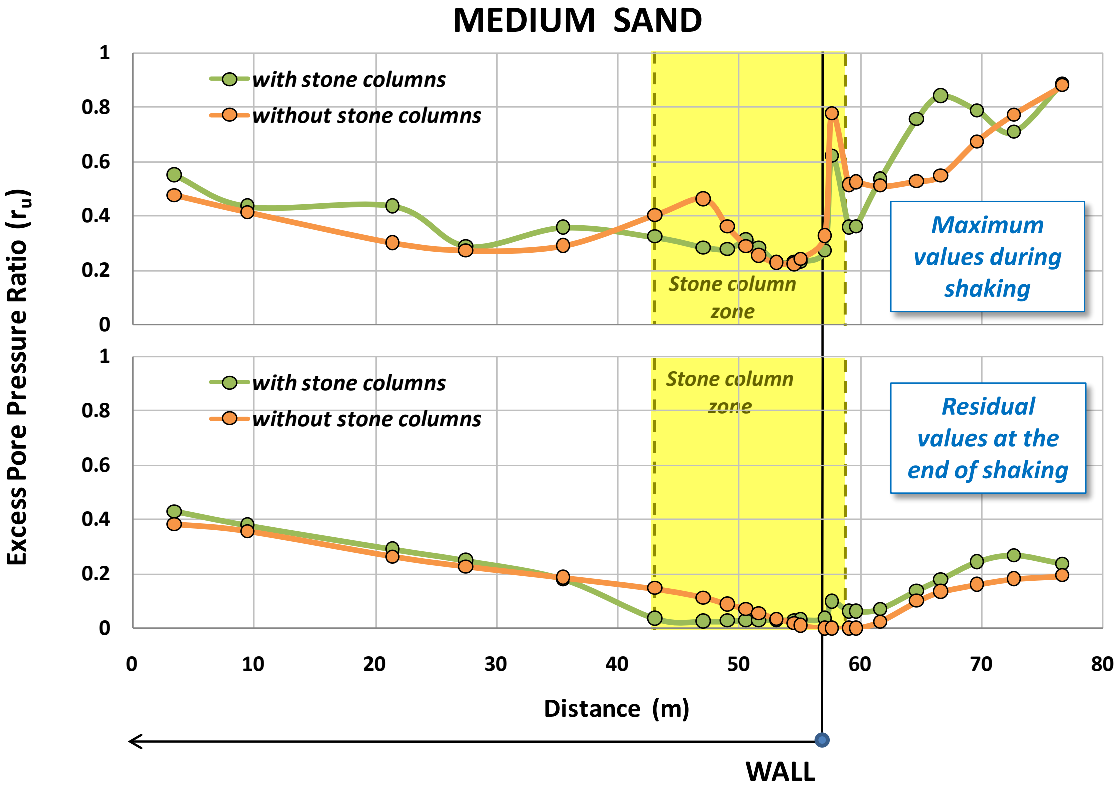

Figure 5. Distribution of maximum and residual excess pore pressure ratios along the medium sand layer *with* and *without* stone columns.

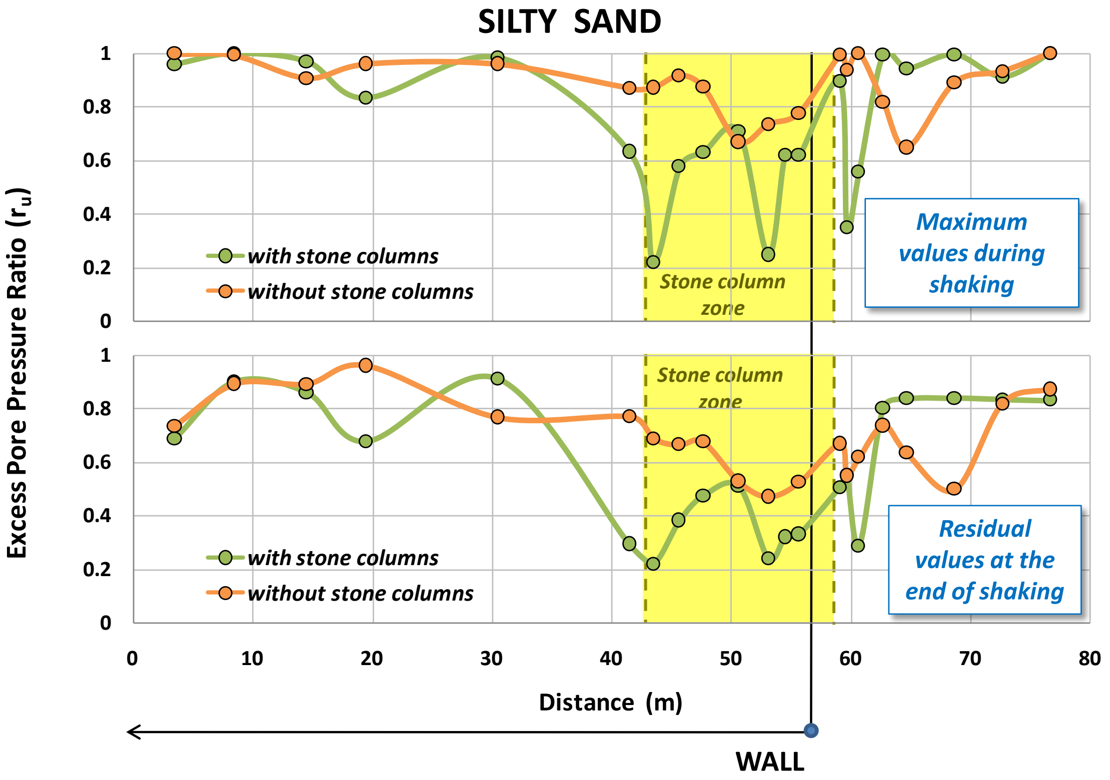

Figure 6. Distribution of maximum and residual excess pore pressure ratios along the silty sand layer *with* and *without* stone columns.