Interaction of stone column and surrounding soil during its construction: 3D numerical analysis

Interaction d'une colonne ballastée et du sol environnant pendant sa construction : analyse numérique 3D

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ABSTRACT: This work deals with a simulation of a construction sequence of a stone column in two distinct stages: a) a one stage excavation and b) a multi-stage backfilling of the column stone excavation with crushed gravel at ascending steps of 1m. Simulation of this procedure is attempted using a 3D model which represents the stone column and the surrounding soil. Analysis is carried out using a numerical code, called FLAC3D, based on finite differences. The mathematical model incorporates geometry and boundary conditions of the problem, profile of soil layers with their physical, deformational and mechanical properties and their constitutive laws, as well as, initial conditions of stresses and deformations of subsoil stratums of the examined area. Special emphasis is given to simulation of an harmonically imposed vertical loading of the vibrating column, into an equivalent static vertical loading and subsequently into an equivalent radial pressure against internal wall of the cylindrical excavation of the constructed stone column. Results clearly denote that there is a strong interaction of the complex system in the kinematical and stress field, which satisfactorily justifies modification of the final diameter of the constructed stone column compared to the theoretical proposed diameter.

RÉSUMÉ : Ce travail se réfère à une simulation numérique de la séquence de construction d'une colonne ballastée, en deux étapes séparées : a) une étape unique d'excavation, et b) plusieurs pas successifs de remblayage de l'excavation cylindrique de la colonne ballastée, avec du matériau granulaire écrasé, à des pas montants de 1m. La simulation est effectuée à l'aide d'un modèle 3D qui représente la colonne ballastée et le sol environnant. Le code numérique utilisé est FLAC3D et il est basé sur le modèle des différences finies. Le modèle mathématique intègre la géometrie et les conditions limites du problème, le profil du sol avec leurs propriétés physiques, mécaniques et de déformation, ainsi que leurs lois de comportement et les conditions initiales de la région examinée. Une attention particulière est donnée à la simulation d'un chargement harmonique vertical imposé à la colonne vibrante, à un chargement équivalent vertical statique, et par la suite, à une pression équivalente radiale exercée sur l'intérieur de l'excavation cylindrique de la colonne ballastée construite. Les résultats démontrent clairement l'interaction prononcée du système complexe, qui justifie aisément le grossissement du diamètre construit par rapport au diamètre théorique conçu lors du dimensionnement du projet.

KEYWORDS: stone column, excavation, multi-stage backfilling, Flac3D, interaction, complex system, diameter.

5 INTRODUCTION – SCOPE OF THE WORK

The present work focuses on the investigation of kinematic and strain interaction of a complex system consisting of a single column stone and the surrounding soil, during the excavation stage and the backfilling stage with crushed gravel.

The scope of this work is the investigation and a possible explanation of the problem concerning modification of the constructed stone column diameter, versus the theoretical (design) one, taking into account the procedure of the stone column construction, its geometrical characteristics and the geotechnical model representing the surrounding soil and its physical, deformational and mechanical properties.

In the framework of this work, a summary of geological, geophysical, geotechnical and seismological data are presented in a succinct way in the following chapters, for the examined area, based on a number of corresponding projects performed in the recent past. After a short technical description of the stone column constructing procedure adopted for this project, the numerical model is determined and numerical analyses results are presented, in an attempt to explain the deduced discrepancy between "constructed" and "designed" stone column diameter. The examined area is located in the wide bed of a river in northern Greece, prone to liquefy, where a bridge is founded.

2. GEOLOGICAL AND SEISMIOLOGICAL DESCRIPTION OF THE STE

According to geological and geotechnical data, resulting from preceding investigation projects on this area, the surface is covered by deposits that belong to the Quaternary and is subdivided into: a) river deposits (RD) consisting of silty sands, clay-silty sands, gravels and locally cobbles of gneiss or marble, and b) alluvial deposits (AL), consisting mainly of sands with a largely fluctuating percentage of clays, silts and gravels, of a thickness ranging from 12 to almost 55m.

The geological bedrock of the examined site consists of rocks of the alpic age and belongs to the Rodopic Mass, consisting mainly of biotitic gneisses (gn) interpolated by amphibolites and marbles green-gray coloured. The upper part of the gneissic rockmass appears intensively weathered to totally weathered, consisting thus the weathering zone of 2 to 4m of thickness. The permeability of different geological formations is quite heterogeneous: the riverbed deposits, mainly gravel consisting (RDg) are a rather permeable soil formation ($k \geq 10^{-3} m/\sec$), whilst alluvial deposits present a rather low permeability ($10^{-7} \leq k \leq 10^{-5} m/\sec$).

As for the seismological data, the examined site belongs to zone I of low seismic hazard, with a horizontal free-field peak ground acceleration value: a_{max}=0.16g, according to the most recent Hellenic map of seismic zones, valid from 1/1/2004.

3. GEOTECHNICAL CHARACTERIZATION

According to the entity of the geotechnical and geophysical investigation programs performed on the broad area (geotechnical boreholes, CPTs and Cross-Hole tests), it results that the prevailing soil formation are alluvial deposits consisting of sands to silty sands, with a high degree of heterogeneity, characterized by USCS as SP, SW, SM, SM-SP, SM-SW. In some cases they appear as clayey sand (SC) to sandy clay (CL), whereas in other cases, they turn out to be gravel layers, such as: GP, GW, GM, GP-GM. According to the almost 200 SPTs performed, the mean value of blows was calculated about 23, with a standard deviation of $\pm$11. The whole area, where the bridge is founded, has been initially divided into three sub-regions represented each by a different geotechnical design section (ITSAK & Gazetas 2003), and finally a design geotechnical section has been attributed to each bridge pier (Edafomichaniki 2007) used for dynamic analyses purposes.

From various simplified design geotechnical sections, each per bridge pier, it has been chosen one, for the needs of the present project, corresponding to a precise pier of the bridge, as being the most representative of the area, but not the most conservative one. The soil profile used in the present work, can be described as follows:

Layer S_{1A} (0 το 2m): loose to medium dense gravels with sand and sand or silty sand with local presence of gravels (GP, SW-SM, SP): $N_{SPT} \cong 22$, γ=20.5kN/m^3, φ'=36^0, c'=3kPa, E_s=10MPa, ν=0.33

Layer S_{1B} (2 to 5m): medium dense gravels with sand and sand to silty sand with local presence of gravels (GP, SW-SM, SP): $N_{SPT} \cong 23$, γ=20.5kN/m^3, φ'=37^0, c'=5kPa, E_s=12MPa, ν=0.32

Layer S_{2A} (5 to 12m): medium dense gravels with silt and sand to silty sand with presence of gravels (GM-GP, SP-SM, SM): $N_{SPT} \cong 25$, γ=21.0kN/m^3, φ'=39^0, c'=6kPa, E_s=16MPa, ν=0.31

Layer S_{2B} (12 to 19m): medium dense silty gravels, silty sand with presence of gravels to silty sand (GM-GP, SP-SM, SM): $N_{SPT} \cong 28$, γ=21.0kN/m^3, φ'=40^0, c'=8kPa, E_s=20MPa, ν=0.30

Layer S_{3A} (19 to 23m) and layer S_{3B} (23 to 35m): medium dense clayey sand-gravels mixture to sandy clay with gravels, or silty sand-gravels mixture (GC-GM, SM, CL): $N_{SPT} \cong 26$, γ=21.2kN/m^3, φ'=37^0, c'=12kPa, E_s=15MPa, ν=0.31.

From 35 to almost 48m the weathering zone of the gneissic bedrock or highly weathered gneiss is met.

4. METHODOLOGICAL APPROACH

The analysis was carried out with FLAC 3D numerical code of finite differences.

4.1 Modeling Procedure

By considering the construction of a stone column in the above soil profile, simulation of two distinct stages of the construction of a stone column is attempted using a three-dimensional (3D) model which represents the stone column and the surrounding soil. Simulation of soil materials is realized by a 3-diamensional polyhedral grid with use of the finite difference method. The mathematical model adopted, incorporates geometry and boundary conditions of the problem, the profile of soil layers, physical, deformational and mechanical properties, constitutive laws for the geomaterials, as well as, initial conditions of stresses and deformations of the subsoil stratums of the area under study.

Geometry of the problem is simplified to axial symmetry. A vertical plane through stone column axis is a plane of symmetry for the analysis. Model grid is shown in figure (1). Coordinate axes are located with origin at the base of the grid, whereas y-axis is oriented along vertical column axis and upward. The initial grid is assigned by 5.0m and 50 units in x-direction, by 5.0m and 50 units in z-direction and by 28.0m and 56 units of in y-direction. A Mohr-Coulomb constitutive model elastoplastic behavior is assigned to all zones of soil surrounding stone column, whilst linear elastic one is assigned to stone column backfilling crushed material. Boundary conditions consist of roller boundaries along the external grid sides of column axis and a fixed base. Equilibrium conditions for initial stresses are based on earth pressure coefficient at rest K_o=ν/(1-ν), where ν: Poisson's ratio.

The modeling sequence consists of the following stages:

Stage I : Initial stresses

Establish equilibrium conditions to initialize stresses

Stage II : Excavation

Stone column excavation at full penetration depth was decided to be numerically simulated in one and only stage, since in reality, excavation was accomplished in about 30 min for a typical stone column of the project, and also, because no steps of excavation during its construction, could be discretized.

Stage III : Stone Column Construction

In reality, construction of cylindrical stone columns of the project with a theoretical diameter D=0.8m and a length L=23.0m, is realized by ascending steps of 0.5m; at each step, the crushed geomaterials are driven through the top of the stone column downwards (top feed method), and then, the vibrational torpedo is sinked into the excavated cyclic area, reaches the top of the crushed material and starts vibrating harmonically at a frequence of 30Hz, in order to achieve an harmonically applied normal stress of 30 to 35MPa. However, our choice of computational ascending steps to simulate stone column construction was of 1.0m, since an initial comparative study between 0.5m and 1.0m ascending steps, revealed no significant differences, whereas computational time difference was important. Therefore, Stage III is sub-divided in two distinct calculation steps, ever after named as "Sub-stage IIIa and IIIb"

Sub-stage IIIa : Simulation of Vibration and Compaction

Based on the construction procedure concerning the one stage of excavation of the stone column to be realized, which affects significantly the mechanical properties of the surrounding zone, a weak zone boundary has been created, by reducing φ' & c', in a distance of 0.60m surrounding column lateral sides, in order to simulate relaxation due to excavation. The width of the weak zone, the reduced values of the mechanical parameters and the elastic deformation modulus, resulted from a "trial and error" back calculating procedure, based on the quantity of the crushed material measured in situ, during the construction of a stone column of the project. Namely, we tried to match the increase of the "as built" diameter of the examined stone column, in agreement with the quantity of the crushed material used for the construction of the stone column, by adjusting the values of mechanical and deformational parameters of the disturbed zone. Vertical normal stress, harmonically applied on top of filling crushed material in order to compact the crushed fill material, per numerical ascending step of the stone column construction, is transferred as a lateral pressure "p" to simulate subjected compressive lateral loads of material due to gravel compaction, in terms of an "equivalent static" lateral (radial) pressure, as explained in the following paragraph.

Sub-stage IIIb : Simulation of Crushed Stone Material filling

This sub-stage simulates filling of the stone column crushed material taking under consideration the preceding compaction procedure. In order to maintain the shape of the "deformed diameter" per constructed step of the stone column, crushed fill material, considered as a linear elastic one, it has been attributed a very high modulus of elasticity, avoiding thus a rebound of the plastic lateral displacements obtained from sub-stage IIIa.

4.2 Assessment of equivalent lateral static loading

It is widely known in Mechanics, that a dynamic system responds to an harmonic external loading, according to the following equation:

$$u(f) = u_{st} \frac{1}{\sqrt{\left[1-(f/f_1)^2\right]^2 + 4\zeta^2}} \tag{1}$$

where, u(f): dynamic displacement, u_{st} : equivalent static displacement (=P/K), ω: frequency of the input motion, ω_1:

predominant frequency of the system (herein: the soil column overlying gneissic bedrock), and ζ: damping ratio of the system.

Figure 1. Model grid used for 3D numerical analyses.

From equation (1), it results that ratio $u(f)/u_{st}$ is greater than 1.0 when $f/f_1<1.0$, and vice versa, when $f/f_1>>1.0$. In this last case, it results:

$$u(f)/u_{st} \cong 1\big/(f/f_1)^2 < 1 \tag{2}$$

Based on the aforementioned, in order to use an "equivalent static" loading instead of a dynamic or harmonic one, we need to use a coefficient b(f), defined as in equation 2. As b(f) is proportional to $u(f)/u_{st}$, it is evident that it will be inversely proportional to loadings, i.e. the ratio $P_{st}/P(f)$. Therefore:

$$b(f) \equiv \frac{P(f)}{P_{st}} = \frac{1}{\sqrt{\left[1-(f/f_1)^2\right]^2 + 4\zeta^2}} \tag{3}$$

In the present problem, it can be assumed approximatively, that:

$$f_1 \cong V_{La}\big/4H \cong 3V_S\big/8H \tag{4}$$

where, V_{La}: wave velocity according to Lysmer ($V_{La}\approx 1.5V_S$), V_S: shear wave velocity, and H: depth of the soil column overlying the gneissic bedrock.

Consequently, for the examined case , where a mean depth of the soil column is admitted as: H=30m and $V_{S30}\approx$250m/sec, the predominant frequency of the system for vertically induced harmonic external loading, can be roughly approximated, as:

$$f_1 \approx \frac{3\times 250m/s}{8\times 30m} = 3\,Hz \tag{5}$$

For input motion frequencies ranging from 20 to 35Hz (mean estimated value of 30Hz) and mean estimated value of damping ratio ζ=20% (Mylonakis et al 2006), equation (3) results b≈0.15, which represents a reductional coefficient due to the frequency of the input motion. It is estimated that due to a large number of uncertainties of the system, and also because the examined system is not a single degree freedom oscillator, it would be wiser to impose a factor of safety of 2.0, resulting thus to a design coefficient b_{design}=b x 2 = 0.3. Accordingly, it results that $P_{st}\approx 30\%P_{cyclic}$.

Based on the above, vertical harmonic loading imposed by a hydraulic vibrating torpedo, can be calculated via cyclic normal stress (30 to 35MPa) applied through the edge of the vibrating column of a diameter d=0.40m. The vertical harmonic loading, is calculated, as follows:

$$P_{cyclic} = q_{cyclic}\frac{\pi d^2}{4} = 30x\frac{3.14x0.4^2}{4} = 3.768MN \tag{6}$$

providing thus an equivalent static vertical loading $P_{st}\approx 30\%P_{cyclic}$=0.3 x 3.768≈1.13MN, and an equivalent vertical normal stress that is estimated to compact vertically the crushed fill material of the stone column at every step of construction:

$$\sigma_{z,st} = \frac{1130x4}{3.14x0.8^2} \cong 1777kPa \tag{7}$$

According to linear elastic theory, earth pressure coefficient at rest, equals to: k_0 = ν/(1-ν) = 0.3/(1.0-0.3)≈0.429, and then the equivalent radial (horizontal) static normal stress is estimated σ'_h = 0.429 x 1777≈762kPa.
For the numerical analyses performed, for the deeper part of the stone column it was adopted a radial pressure of 750 to 800kPa, whereas, it has been progressively reduced as ascending steps of stone column construction were getting close to the head of the stone column at free surface until it has almost been nullified in the last step.

5. NUMERICAL ANALYSIS IMPLEMENTATION & RESULTS

Developing a step by step simulation of a stone column construction (excavation, filling & compaction), analysis results are mainly concentrated to the plasticity limits of soil strength and to the outwards lateral displacement of the stone column excavated sides due to gravel compaction. Plasticity indicators for shear or tension are divided at a present plastic yield indicator with symbol (–n) or a past plastic yield indicator with symbol (–p). Outwards lateral displacement are being recorded at every depth level of the stone column, in different grid points with distance of 0, 30cm, 60cm and 100cm of the excavated sides of the stone column.

Figure (2) shows plasticity indicators generated due to the excavation at full penetration depth. It can be seen that one step column excavation, has no remarkable effect at inwards horizontal displacements. At this case, plasticity limits of soil strength developed in a distance of 0.20-0.40m surrounded excavated sides. Inwards horizontal displacements of the excavation are limited in a range of 4-5mm with maximum values appearing at deeper levels of excavation.
Sub-stages IIIa & IIIb simulate the compaction/filling of crushed stone material and interaction of the above to surrounding soil. Figures (3) and (4) exhibit plasticity indicators for two different construction depths from 16m to 15m and from 1m up to the head of the stone column (free soil surface) respectively. Although, most of plastic indicators, reveal a past plastic yield (indicator –p) in shear or tension, plasticity disturbance of the soil is generated in a remarkable distance of 1.0 to 1.2m surrounding column sides for the first example and in almost the entire surface area of the surrounding soil at the second one. Low initial stress state at free soil surface, leads to a remarkable plastic yield over limit close to the stone column head, even though equivalent static normal radial stress is very low. Concerning lateral outwards displacement of stone column excavated sides, due to gravel compaction/filling, shows that values between 10 and 20cm keep well at a distance of 100cm of the excavated sides. Indicatively, outwards radial displacement values (at excavated sides) for depths at 22.5m, 11.0m and 1.0m are in a size of 23cm, 12cm and 20cm respectively. In general terms, outwards horizontal displacements are eliminated at distances more than 60cm of excavated sides.

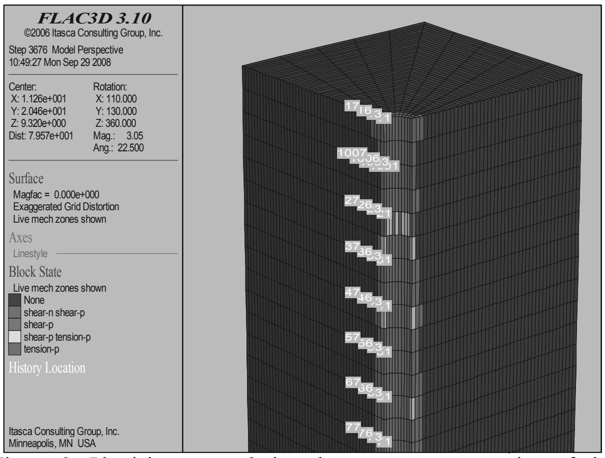

Figure 2. Plasticity zones during the one stage excavation of the examined stone column

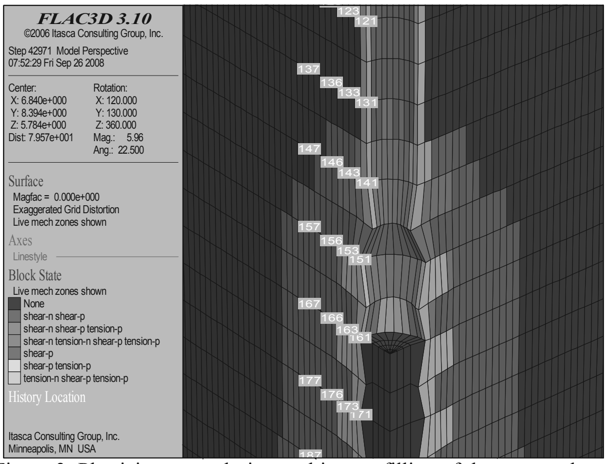

Figure 3. Plasticity zones during multi-stage filling of the stone column with crushed geomaterial at depth of 16 to 15m simulated by an equivalent static radial pressure (sub-stage IIIa, 8th ascending step of construction of the examined stone column)

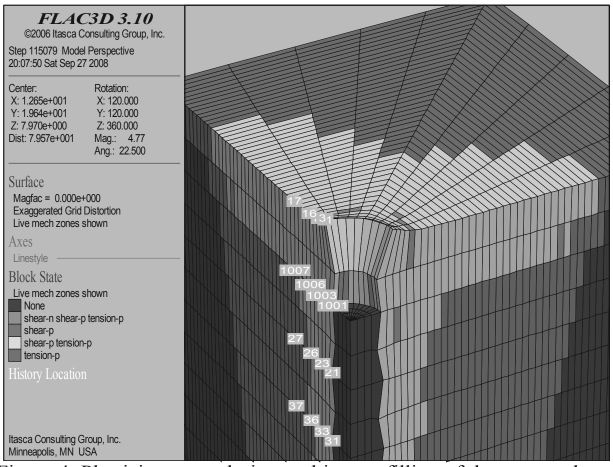

Figure 4. Plasticity zones during multi-stage filling of the stone column with crushed geomaterial at depth of 1m to head of the stone column, simulated by an equivalent static radial pressure (sub-stage IIIa, 23rd final ascending step of construction of the examined stone column)

6. CONCLUDING REMARKS

For the needs of the present project it has been decided to adopt a rather simple, yet representative, soil profile corresponding to a bridge pier, where typical stone columns of 0.8m diameter and 23m length are constructed, in order to improve foundation soil behaviour. The complex system consisting of a stone column and the surrounding soil is numerically analyzed with FLAC3D numerical code based on finite differences.

The numerical code used considered the procedure of construction, as well as, its effects on the surrounding soil, and simulated at its best, the physical procedure of the stone column construction, in a rational and well documented way.

Excavation stage is simulated in one and unique stage, whereas, construction of a stone column is simulated by a multi-stage complex procedure divided in two distinct calculating steps. Those are identified as two sub-stages per ascending step of construction: a) vibration and compaction, materialized by application of an equivalent radial pressure against the internal wall of the cylindrical excavation and b) stone column filling with a linear elastic geomaterial assigned a high elastic modulus of compressibility, due to the compaction procedure, preventing a rebound of the induced radial displacements of the first sub-stage.

Commenting the outcome of numerical analyses performed, the following points can be outlined:

1. after completion of excavation stage, the plastic zones developed around the cylidrical excavation are limited, same as horizontal displacements, ranging from some millimeters to only a few centimeters,
2. once excavation procedure is completed, it has been documented via a “trial and error” back calculating procedure, that a zone of about 60cm is seriously disturbed, affecting notably the mechanical and deformational parameters of the surrounding soil,
3. the stage of constuction of the stone column has been simulated by a multi-stage procedure of ascending steps of 1m and application of an equivalent static radial pressure, as defined in §4.2, progressively reduced as ascending construction steps approached the head of the stone column at the free surface,
4. horizontal inelastic displacements in the limit of the side wall of the cylidrical excavation range between 10 and 20cm, resulting thus in an expansion of the constructed diameter, compared to the theoretical one as designed.

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