Numerical assessment of the seismic performance of a Terre Armée retaining wall: a comparative study between non extensible and extensible reinforcements

Y. Bennani ⁱ⁾, L. Lenti ⁱⁱ⁾ and N. Freitag ⁱⁱⁱ⁾

i) Engineer, Technical & Scientific department, Terre Armée, 280, Avenue Napoléon Bonaparte, Rueil Malmaison 92506, France.

ii) Researcher, Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR), 14-20, bd Newton, Cité Descartes, Champs sur Marne F-77447, Marne la Vallée Cedex 2, France

iii) Deputy Manager, Terre Armée, 280, Avenue Napoléon Bonaparte, Rueil Malmaison 92506, France.

ABSTRACT

Over the world Terre Armée retaining walls have demonstrated impressively high performances after being submitted to very strong earthquakes. Sites investigations on 1,423 Terre Armée structures in Japan after the Great East Japan Earthquake of 2011 revealed that they present an impressive robustness and efficiency. Only 4 failures were observed, either caused by a lack of protection against scouring induced by the passage of the strong tsunami wave or caused by a general sliding. In Japan, the majority of Terre Armée retaining walls are built using High Adherence steel reinforcements. However, steel reinforcement cannot be used in marine areas or highly corrosive environments. For such aggressive environments synthetic reinforcements made of high tenacity fibers with a high stiffness are preferred. Our feedback on such structure exposed to earthquake motions is very positive, but not as well reference as for structures reinforced with steel. Nevertheless efforts are still needed to assess their performance under very strong motions.

This paper introduces a numerical dynamic analysis to study Terre Armée retaining walls response to seismic loads. An overview of the modelling aspects will be given and the impacts of the reinforcement stiffness on the seismic performance will be shown. The paper will bring a relative comparison between the behavior of a wall reinforced with non-extensible reinforcements and a wall reinforced with relatively more extensible ones.

Keywords: earthquake, reinforced earth walls, seismic performance, numerical analysis

1 INTRODUCTION

Terre Armée (TA) structures, by being both heavy and flexible, resist very well to vibration and to seismic loads. Recent strong Earthquakes such as the Great East Japan one in March 2011 demonstrate their excellent performances (Otani, Y & al. 2011). A great part of the available worldwide feedback is based on structures reinforced with High Adherence non extensible steel strips, *HAR* (see figure 1), however for durability reasons extensible synthetic strips shall be used in some highly corrosive environments and the performances of such structures still need to be assessed.

Fig. 1. Left: HAR steel strip; Right: GeoStrap reinforcement (synthetic)

With the continuous rising power of computers, numerical methods represent nowadays an important tool to assess the possible behaviour of T.A structures to seismic loads. A research investigation using FLAC 2D was therefore carried out to assess the comparative performance of structures reinforced with extensible and inextensible strips under a seismic motion. This paper presents an overview of the numerical model used in this analysis. A particular attention is given to how the soil model parameters were assigned, the reinforcement stiffness was obtained, the strip / soil interaction was determined, and how the ground motion was defined in the modelling. A comparison between the results related to a structure with steel strips and a structure with stiff synthetic reinforcements is then presented.

2 MATERIALS PROPERTIES UNDER DYNAMIC LOADING

Properties of a TA components wall may be influenced by the rate / amplitude of the loading and by the cyclic loading response. This section reviews data and models that can be used for the dynamic simulation.

2.1 Reinforcements

Because the material temperature remains low, reinforcements made of steel are not influenced by the dynamic loading induced by the seismic motion. However Terre Armée GeoStrap® strips, made of high tenacity polyester (PET) yarns, exhibit a different behavior according to the dynamic load. Figures 2 to 3 illustrate respectively the influence of the load frequency and of the load amplitude on the stiffness (ES) of a polyester yarn (1500 Decitex-150filaments). Unload/reload tests at different frequencies and amplitudes clearly indicate that the yarn behavior is frequency independent and strain amplitude dependent.

Fig. 2. T.A cyclic load testing at varying frequencies on a PET yarn.

Fig. 3. T.A cyclic load testing at varying load amplitudes on a PET yarn.

The energy loss, which is related to the area inside the nonlinear hysteretic loops in Figure 3 increases with an increasing load amplitude.

Because the reinforcements are assumed to work at

around 30% of their characteristic ultimate strength, the secant modulus computed at 30% of the UTS in Figure 4 can be used to simulate the short term behavior of the structure. For a long term behavior isochronous curves are used to consider creep under constant load. For instance, during a seismic calculation, if it is assumed that the deformation increment of the strip remains below 0.8%, the yarn short term stiffness during the dynamic simulation can be increased by a ratio of 2,6 as indicated in equation (1).

$$\text{Ratio} = \frac{ES_{\text{dynamic}}}{ES_{\text{static}}} = \frac{2466\text{N}}{953\text{N}} = 2,6 \quad (1)$$

If the long term stiffness is used to model the ante-earthquake static state of the structure, this ratio will have to be raised 3,3.

Fig. 4. Monotonic test on a PET yarn.

2.2 Soil / reinforcement interaction

Pullout tests and direct shear box tests are used to define the soil / reinforcement interaction via the apparent friction coefficient. In the literature relatively few results related to the effect of repeated tensile loads on apparent friction coefficient are available.

For geosynthetics, the little information found in the literature on direct shear strength tests on geotextiles (Myles, 1982), or on HDPE sheets (O'Rourke & al., 1990), indicate that for dry cohesionless soils there is no reduction in the interface shear strength with the number of shear applications. Some large scale pullout tests on stiff uniaxial HDPE geogrid on standard #40 laboratory silica sand (Bathurst & McLay, 1996), subjected to repeated tensile load and constant overburden pressure (>25 kPa), indicate that full shear mobilization along the tested specimen was never reached, and that the displacement measured at the front end of the grid diminishes with the log number of load applications (in certain cases up to 90 000 load applications).

Based on our experience on TA walls that were

already subjected to strong earthquakes, on what can be found in the literature, and on the expectation that soil/soil interface shear capacity for dry cohesion less soils is independent of the rate of loading, it seemed reasonable for the authors to consider results of monotonic loading pullout tests for the definition of soil/reinforcement interaction (both with synthetic and metallic reinforcements).

2.1 Soil elastic properties

In soil mechanics the dynamic properties of soils are defined thanks to the shear wave velocity through the medium. Table 1 extracted from Eurocode 8 (EN 1998-1, table 3.1) provides some indications about the average shear wave velocity, V_{s30} , along a 30m thick medium.

Table 1. Test conditions.

Soil profile name	V_{s30}	SPT N-Value
Hard Rock	> 1500 m/s	---
Rock	760 to 1500 m/s	---
Very Dense Soil & Soft Rock	360 to 760 m/s	> 50
Stiff Soil	180 to 360 m/s	15 - 50
Soft Soil	< 180 m/s	< 15

In order to better capture the true soil behavior, the initial soil shear modulus was taken as a function of the depth. Furthermore the technical backfill being very dense and frictional soil, equation (2) was used for the definition of the initial shear modulus. This equation leads to V_{s30} about 475m/s.

$$G_{\max} = \min(60; 33 \cdot \sqrt{\text{depth}}) \text{ (MPa)} \quad (2)$$

The Poisson ratio was taken as a constant equal to 0.33.

2.1 Soil damping

A monitoring of the shear stress and strain behavior related to a soil sample under cyclic triaxial test will lead to the curve presented in Figure 5. This figure indicates that for a “closed cycle”, the soil behavior exhibits a loop called hysteresis. The amplitude and the surface of this loop depend on the strain amplitude during the cycle. The greater the amplitude is, the greater is the loop area and smaller is the mean inclination of the hysteretic loop referred to the horizontal. Moreover it was experimentally noticed that, as a first approximation, the hysteresis is not affected by the loading rate. The hysteresis during the closed loading cycle reveals the energy dissipation in the material. The damping is used to describe the kinetic and potential energy transformation into heat. Damping is due to the loss of mechanical energy as a result of internal friction process in the intact material. It is the damping that allows a

physical system under vibration at its natural frequency to maintain limited amplitudes of displacement.

Fig. 5. Shear stress/strain path from a cyclic triaxial test.

FLAC enables the use of strain (γ)-dependent modulus (G_s) formulations (see equation (3)) and their related strain-dependent damping functions during the finite differences modeling. This strain dependent functions try to represent the main features of the nonlinearity effects in soils during severe earthquakes.

$$G_s = y_0 + \frac{a}{1 + \exp\left(-\frac{L - x_0}{b}\right)} \text{ and } L = \log_{10}(\gamma) \quad (3)$$

For our simulation a hysteretic damping was preferred to the usual Rayleigh damping. The following parameters were used in equation (3): $a = 0.9$; $y_0 = 0.1$; $x_0 = -1.249$; $b = -0.4792$; figure 6 and 7 illustrate the obtained shear modulus reduction ratio and its associated damping. It is very hard to fit well both the ratio and the damping curve to Seed and Idriss upper and lower bound curves.

Fig. 6. Shear modulus reduction curve.

Fig. 7. Damping ratio curve.

3 SPECIFICATIONS OF INPUT MOTION

Dynamic analysis can be performed with FLAC, wherein user-specified acceleration, velocity, stress time-histories can be input. In the here presented analysis, taking into account that the modeled structure is not founded on a very hard rock, a quite boundary condition was chosen to apply the seismic solicitation. As a consequence the input dynamic motion was represented by a stress time history. The earthquake ground motions, almost all the time are known at the free surface of the outcropping rock formation and for that reason they are also called reference outcrop motions. For a numerical simulation, the input motion is applied at the base of the model rather than at the ground surface (see figure 8). In order to obtain the correct input motion at any layer of the soil profile a deconvolution procedure can be done by SHAKE91 (Idriss & Sun 1992) or with equivalent software.

Fig. 8. Schematic location of the outcrop and input motions.

For computation time reasons, only the upper 9m of an 18m deep profile was modeled inside FLAC. In order to consider the influence of the layers below the 9m the entire soil profile was modelled using an equivalent version to SHAKE software. The interlayer motion, also called as the within motion, at the depth corresponding to the base of the FLAC model was calculated.

The free-field acceleration time-history of El Centro earthquake (1945) was chosen for the case study (see figure 9). A frequency cut-off of 20Hz was estimated from the frequency content of the outcrop motion. Removing high frequencies allows coarser mesh to be used and therefore a significant saving of calculation time while maintaining a good wave transmission inside the medium. Moreover, at large strains, the fundamental frequency of the system was estimated to be around 4Hz which is lower than the frequency cut-off. Residual displacements, finding their origin in very low frequency waves, were removed applying to the motion resulted from the deconvolution software a high pass 4 poles Butterworth filter.

Fig. 9. Acceleration time-history of El Centro earthquake (1945)

4 CASE STUDY

As explained earlier, depending on the soil corrosivity, galvanized steel or synthetic strips (geostrips) can be used. The behavior of structures being well known with metallic strips but to a lesser extent with geostrips, a comparative study between the performances of both structures was carried out. Synthetic reinforcements were taken in this analysis 31 times (GeoStrap) as soft as steel strips.

4.1 Model geometry and zone size

The model consists in a 10.5m Terre Armée retaining wall founded on a 9m deep foundation. The model extends laterally on 77.5m including 17.5m of the foundation soil in front of the wall and 7.5m technical fills which compose the mechanically stabilized earth wall (see figure 10)

Fig. 10. Geometrical and size features of the case study.

In order to ensure a good transmission of the waves inside the soil mass, the maximum zone size should be limited in the FLAC model. In order to account for the degradation of the shear moduli during the earthquake and therefore to account for a reduction of the shear wave velocities, C_s , the maximum zone size is consequently evaluated considering the non-linearity. A maximum zone size of 72cm was defined using equation (4) given in FLAC manual. For the FLAC analysis performed in the case study, 25cm by 25cm zones were used uniformly in the model.

$$\Delta l = \frac{C_{s,\min}}{10 \cdot f_{\max}} \quad (4)$$

4.2 Static state equilibrium prior to shaking

Before the dynamic simulation, the static equilibrium state of the TA structure is first obtained through the simulation of the stepped construction of the wall. The foundation soil stresses, velocities and displacements are first initialized, and then the first row of discrete panels (1.5m high by 1.5m wide) is placed followed by the installation of the first strip and backfill layer. A second layer of backfill and strip is then placed again after having reached the static equilibrium of the previous step. These steps and their static equilibrium are reiterated until the end of the retaining wall construction.

5 CASE STUDY RESULTS

Hysteretic damping is supposed to take place in conjunction with an elasto-plastic constitutive soil model to allow plastic deformation to occur whenever the dynamic shear stresses exceed the shear strength of the soil. Some first runs were showing unrealistically high deformations that cannot be correlated to structures being already submitted to stronger earthquakes. It was therefore decided to use a non-plastic soil model in conjunction with the hysteretic damping.

5.1 Residual displacements

Figure 11 and 12 illustrate the residual horizontal displacements recorded at the end of the earthquake for the two wall configurations (HA steel strips, GeoStrap). It can be pointed that with an increasing reinforcement stiffness a decreasing residual displacement is obtained.

Fig. 11. Residual displacement with High Adherence steel strips

Fig. 12. Residual displacement with GeoStrap reinforcements

Table 2 summarizes the maximum residual horizontal displacement and the ratio between steel strips stiffness with the synthetic reinforcement stiffness. Even if steel strip stiffness is 31 times higher compared to the stiffness of the GeoStrap, the deviation of the maximum residual displacements between the two walls is low.

Table 2. Residual displacements and stiffness relatively to steel strips.

Reinforcement	Relative stiffness	Relative maximum residual displacement
Steel strip	1.0	1.0
GeoStrap (synthetic)	31.0	2.2

5.1 Over tensioning induced by the motion

Figure 13 illustrates the over-tensioning induced by the earthquake for all the strip layers (difference between dashed and straight lines). As it could have been expected the stiffer is the reinforcement the higher are the incremental tensions.

Fig. 13. Highest maximum tensions recorded in the reinforcements during the earthquake compared to the static maximum tensions

5 CONCLUSIONS

The authors outline some key details of a numerical modelling of a Terre Armée structure for use in computing dynamic response to an earthquake. Due to some strong assumptions taken, such as a non-plastic soil model, the analysis will have to be limited to comparative analysis and different solutions can be confidently compared within a relative approach.

Relatively to the structure with steel reinforcements, the structures with geostrips show more displacements but behave well under the simulated seismic motion. The deviation of the residual displacement is low even if the stiffness deviation is very high. One possible explanation is that under a seismic motion the soil plays a much more important role than during the wall construction phase (static phase). Moreover a higher soil stiffness combined with stiffer synthetic reinforcements may also contribute in the mitigation of the residual displacement deviation between the two wall configurations.

With respect to the low deformation that was observed on structures reinforced with steel strips under very strong earthquakes and with respect to what was obtained numerically in this report, TA structures with GeoStrap reinforcements can be anticipated to exhibit very good performances.

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