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Seismic performance of bar-mat reinforced-soil retaining wall: Shaking table testing versus numerical analysis with modified kinematic hardening constitutive model

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ABSTRACT

Reinforced-soil retaining structures possess inherent flexibility, and are believed to be insensitive to earthquake shaking. In fact, several such structures have successfully survived destructive earthquakes (Northridge 1994, Kobe 1995, Kocaeli 1999, and Chi-Chi 1999). This paper investigates *experimentally and theoretically* the seismic performance of a typical bar-mat retaining wall. First, a series of reduced-scale shaking table tests are conducted, using a variety of seismic excitations (real records and artificial multi-cycle motions). Then, the problem is analyzed numerically employing the finite element method. A modified kinematic hardening constitutive model is developed and encoded in ABAQUS through a user-defined subroutine. After calibrating the model parameters through laboratory element testing, the retaining walls are analyzed *at model scale*, assuming model parameters appropriate for very *small confining pressures*. After validating the numerical analysis through comparisons with shaking table test results, the problem is re-analyzed *at prototype scale* assuming model parameters for *standard confining pressures*. The results of shaking table testing are thus *indirectly* "converted" (extrapolated) to real scale. It is shown that: (a) for medium intensity motions (typical of $M_s \approx 6$ earthquakes) the response is "*quasi-elastic*", and the permanent lateral displacement in reality could not exceed a few centimeters; (b) for larger intensity motions (typical of $M_s \approx 6.5$–7 earthquakes) bearing the effects of forward rupture directivity or having a large number of strong motion cycles, plastic deformation accumulates and the permanent displacement is of the order of 10–15 cm (at prototype scale); and (c) a large number of strong motion cycles ($N > 30$) of *unrealistically* large amplitude ($A = 1.0$ g) is required to activate a failure wedge behind the region of reinforced soil. Overall, the performance of the bar-mat reinforced-soil walls investigated in this paper is totally acceptable for realistic levels of seismic excitation.

1. Introduction

Invented by the French Architect and Engineer Henri Vidal in the late 50s, "*reinforced earth*" can be characterized as a composite material. It combines the compressive and shear strength of a thoroughly compacted "select" granular fill (with specific requirements concerning grain distribution, fines content, plasticity index, friction angle, etc.) with the tensile strength of reinforcing materials, such as mild steel (e.g. dip galvanized flat ribbed strips or welded wire mats) or geosynthetic polymers (polypropylene, polyethylene, or polyester geogrids, or woven and non-woven geo-textiles). The latter compensates for the weak strength of soil in tension, rendering reinforced earth the direct analog of reinforced concrete in soil. Depending on the nature of the reinforcement, a reinforced earth system may be characterized as inextensible (when the reinforcement fails without stretching as much as the soil) or extensible (when the opposite is true). Inextensible steel reinforcements are most common for critical structures, such as bridge abutments where control of deformation is crucial. On the other hand, extensible geosynthetic reinforcement is often used in reinforced slopes, basal reinforcement, and temporary retaining walls, where there is no concern for displacement.

Reinforced earth retaining walls posses a number of technical and economic advantages compared to standard gravity walls: (a) they can be constructed rapidly, without requiring large construction equipment; (b) they require less site preparation and less space in front of the structure for construction operations, thus reducing the cost of right-of-way acquisition; (c) they do not need rigid foundation support as they are tolerant to deformations; and (d) they are very cost effective and technically feasible even for heights exceeding 25 m. The first such wall in a seismically active area was constructed in California's Sate Highway 39, in 1972. Since then, in recognition of all the

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previously discussed advantages, their use quickly spread universally in highway, industrial, military, commercial, and residential applications.

Reinforced earth structures have all the necessary "ingredients" to be earthquake resistant: being flexible, they tend to follow the dynamic deformation of the retained (free-field) soil without attracting substantially large dynamic earth pressures (e.g. [1]). Indeed, several reinforced soil walls have experienced large intensity destructive earthquakes (Loma Prieta 1989, Northridge 1994, Kobe 1995, Chi-Chi 1999, and Kocaeli 1999) without considerable damage. One of the most dramatic such examples is the 1994 M_w 6.8 Northridge earthquake. With many recorded PGA values higher than 0.60 g, the inflicted damage to structures of all kinds was rather extensive, while 5 major freeway bridges, 18 parking stations, and 40 buildings totally collapsed. Surprisingly, the damage to 23 reinforced soil walls of several heights within the affected area of the earthquake was minor [2]. Regardless of their location and recorded level of PGA, all of them were found to be fully intact with no conspicuous structural damage. Only in one case, minor concrete spalling on the facing panel was observed.

Even more interesting is the performance of reinforced earth walls during the 1995 M_w 7 Kobe earthquake. With recorded PGAs exceeding 0.8 g, the damage was devastating with the direct economic loss exceeding $100 billion [3–6]. The damage to all sorts of structures was more than devastating: from the Kobe Port which was practically put out of service (all but 7 of its 186 berths were totally damaged) to the spectacular overturning structural collapse of a 630 m section the elevated Hanshin Expressway, to countless collapses of bridges and buildings, and to numerous landsides. Also substantial was the damage to a variety of gravity-type retaining structures [7–10]. In marked contrast, damage to reinforced earth walls was rather minor [11,12]. A total of 124 reinforced earth structures, of height ranging from 2 to 17 m were inspected after the earthquake. Although most of them had been designed for ground acceleration of the order of 0.15 g, 74% of them sustained no damage at all, 24% had only very minor damage (mainly displacement), and only 2% showed some damage to the wall facing and movement of the retained soil. No collapse or clear failure was observed.

The seismic performance of reinforced earth structures has been investigated experimentally with various methods: from soil element testing [13], to centrifuge model testing [14–21], and shaking table testing at reduced [22,23], and at nearly full scale [18,24–26]. Among the several conclusions

(i) the critical acceleration is a function of backfill density [21];
(ii) the stiffness, spacing, and length of the reinforcement directly affect the stability and the lateral and vertical deformation of the wall [15,17–19,21];
(iii) the length of the reinforcement is not crucial, as long as it exceeds 70% of the wall height [21];
(iv) the backfill is subjected to substantial densification and settlement [19,21];
(v) current pseudo-static seismic stability analyses based on the limit equilibrium method underestimate their seismic stability [24,27];
(vi) the largest lateral displacement takes place at the middle-height of the wall [19]; and
(vii) finite element (FE) simulation can capture the dynamic response of reinforced earth walls, provided that nonlinear soil response is modeled with a realistic constitutive law [18,25].

This paper investigates *experimentally* and *analytically* the seismic response of typical reinforced soil (bar-mat) retaining walls. First, we present the experimental setup and the key results of a series of reduced-scale shaking table testing. Then, a nonlinear FE model is developed for the same problem. A modified kinematic hardening model is developed and encoded in ABAQUS through a user subroutine. The parameters are calibrated through experimental data (soil element testing of the "*Longstone*" sand used in the experiments): (a) for small confining pressures (which are considered representative for the 1g shaking table tests), and (b) for standard confining pressures (which are considered representative for the prototype problem). First, we analyze the shaking table test (assuming model parameters for small confining pressures) to validate the analysis methodology and the constitutive model. Then, we analyze the prototype (assuming model parameters for standard confining pressures), thus extending our results to the real scale.

2. Shaking table testing

A series of two models were constructed and tested at the Laboratory of Soil Mechanics of the National Technical University of Athens (NTUA), utilizing a recently installed shaking table. The table, 1.3 m $\times$ 1.3 m in dimensions, is capable of shaking specimens of 2 tons at accelerations upto 1.6 g. Synthetic accelerograms, as well as real earthquake records can be simulated. The actuator is equipped with a servo-valve, controlled by an analog inner-loop control system and a digital outer-loop controller; it is capable of producing a stroke of $\pm$75 mm.

At this point, it is noted that the stress field in the backfill soil cannot be correctly reproduced in reduced-scale shaking table testing, and this is the main advantage of centrifuge testing. Its disadvantage, however, is the crude knowledge of soil properties versus depth in most centrifuge tests. Shaking table testing can be seen as a valid option, provided that the results are interpreted carefully, with due consideration to scale effects and the stress-dependent soil behavior.

2.1. Physical model configuration and construction

As shown in Fig. 1, the prototype refers to two reinforced earth retaining walls, both 7.5 m high, positioned back-to-back at 21.4 m distance, supporting a dry granular backfill. Each wall is reinforced with 13 rows of bar-mat grid, at 0.6 m vertical spacing. Following the key conclusions of earlier studies (see discussion above), each reinforcement row is 0.7H long (i.e. 5.12 m in prototype scale). Two types of reinforcemnt were selected: (a) a relatively "flexible" reinforcement grid, consisting of 8 mm bars at 20 cm spacing both in the longitudinal and the transverse direction; and (b) a "stiff" reinforcement grid, consisting of 20 mm bars also at 20 cm spacing. In both cases, the facing panels are made of reinforced concrete, 0.2 m in thickness, and 0.6 m in height.

Taking account of the capacity of the shaking table, a N=20 scale factor was selected for the experiments, resulting to a total height of the model of 49.8 cm. The selection of model materials was conducted taking account of scaling laws [28], as synopsized in Table 1, so that the simulation is as realistic as posible for the given prototype. The bar-mats were constructed using commercially available steel wire mesh: d=0.4 mm at 12 mm spacing, for the "flexible" reinforcement; d=1 mm, also at 12 mm spacing, for the "stiff" reinforcement. Athough the stiffness is not accurately scaled, this selection was made as a compromise between the target stiffness and the scaling in terms of the soil-reinforcement interface (which depends on geometry). The facing panels were made of t=2 mm plexiglass strips ($E \approx 3$ GPa), and were connected to each other through a customized