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SHAKING TABLE TESTS OF SIMPLE DIRECT FOUNDATIONS

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ABSTRACT

A large flexible shear stack, measuring 5m long by 1m wide and 1.2m deep, has been developed to provide data on the behaviour of simple direct foundations subject to seismic loading. The work formed part of the European Union funded PREC8 Network project carrying out pre-normative research for Eurocode 8. The paper describes the design studies for the shear stack and the initial development testing to prove the design concept. The shear stack replicated idealised soil layer boundary conditions and produced non-linear soil behaviour similar to a previous smaller flexible shear stack. The initial results of foundation test programme are outlined.

KEYWORDS:

Shaking table; foundations; shear stack; free field.

INTRODUCTION

The European Union is funding a major Network project, known as PREC8, to carry out pre-normative research for the new seismic code, Eurocode 8. One aspect of the PREC8 project concerns simple direct foundations. These are being studied through a combination of numerical analysis and large scale shaking table tests (Faccioli and Paolucci, 1995). The latter are being carried out under the European Consortium of Earthquake Shaking Tables (ECOEST) at Bristol University. This paper describes the design, development and initial results of the shaking table tests.

Whilst a wide variety of numerical models for modelling the dynamic behaviour of geotechnical problems is available, there are few experimental or prototype data against which these models can be compared. The overall aim of the experimental part of the PREC8 foundations project was to develop a well controlled experimental database that could be used for numerical code validation. Previous research at Bristol University (Taylor, Dar and Crewe, 1994) had proved the concept of a flexible "shear stack" type soil container for shaking table modelling of geotechnical problems. The PREC8 project sought to extend this concept to cater for modelling of simple direct foundations.

SHEAR STACK CONCEPT

The flexible shear stack consisted of a rectangular, laminar box made from aluminium rectangular hollow section rings separated by rubber layers. The aluminium rings provided lateral confinement of the soil, while the rubber layers allowed the stack of rings to deform in a shear beam manner. The mass and stiffness characteristics of the shear stack were carefully chosen so that the stack's natural frequencies and mode shapes in horizontal shear were compatible with those of the soil it contained.

The primary aims of the design were to ensure that the soil mass controlled the overall dynamic response of the soil-stack system and that the soil mass was subjected to the simple shear boundary conditions that are present in the idealised prototype system. The latter is depicted in Fig.1, which shows a horizontal strata of soil overlying rigid bedrock. The lateral boundaries are at infinity. When subjected to horizontal bedrock movements, the soil responds like a shear beam as horizontal shear waves propagate vertically, leading to a sinusoidal lateral displacement profile. Gazetas (1982) studied this problem analytically, producing useful elastic solutions incorporating soil elastic moduli that were dependant on mean confining pressure. A small element in the soil profile is subject to simple shear conditions. When extrapolated to a vertical soil column this leads to boundary shear distributions as indicated in Fig. 1. Thus, the shear stack must allow these lateral deflections to occur with little hindrance and must also allow the generation of complementary shear stresses on the end walls and on the base.

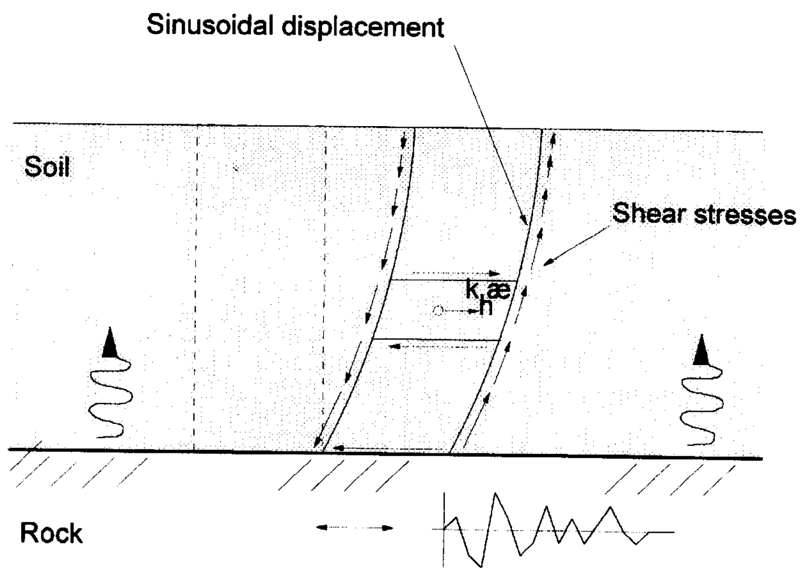

Fig. 1. Theoretical soil deposit response

Taylor, Dar and Crewe (1994) developed a small shear stack measuring approximately 1.2m long by 0.8m high by 0.7m wide. The aluminium rings were separated by solid rubber layers giving the empty shear stack a fundamental frequency of 12Hz. This corresponded to the approximate natural frequency of a dry dense sand sample subjected to shear stains of about 0.5% to 1.0%. They showed that the sand motions were extremely uniform over horizontal planes throughout the specimen, even close the boundaries, and that the lateral displacement profile closely resembled the theoretical profile. A limitation of the Taylor, Dar and Crewe shear stack was that at high strains, when the soil specimen started to fail, the stack remained elastic and gradually dominated the response. This was due to the use of solid rubber layers around the full perimeter of the aluminium rings.

The idealised problem to be studied consisted of a simple rectangular footing on a uniform soil layer of infinite lateral extent, overlying a rigid bedrock. In two dimensions the foundation would be akin to a strip footing. Classical foundation failure models of the Prandtl-type predict non-circular slip surfaces which extend laterally to the order of five times the width of the foundation block. As scaling soil properties correctly in a 1g gravitational field is difficult, the shear stack had to represent conditions at, or close to, prototype scale. These factors, combined with the dimensions and payload capacity of the EPSRC Earthquake Simulator (shaking table) at Bristol University, led to the choice of a shear stack measuring 5m long by 1m wide by 1.2m deep. Such a stack would be capable of modelling a foundation up to 0.5m wide subjected to bearing pressures typical of a two or three storey house. Ideally, the stack should have been at least twice as deep, but this would have taken the payload beyond the capacity of the shaking table.

DESIGN OF THE SHEAR STACK

The final arrangement of the empty shear stack on the shaking table is shown in Fig. 2. The internal dimensions of the stack were 4.8m long by 1.0m wide by 1.2m deep. The 100 x 44 x 3 aluminium RHS rings were restrained laterally by a rigid steel framework supporting a bearing system. Vertical bearings prevented pitching of the stack. The aluminium rings were separated at the end walls and bearing points by soft rubber blocks. This gave the stack a low elastic stiffness and a low natural frequency. It also reduced the problem of the stack being too stiff relative to the soil at high shear strains. Plywood strips were placed between the aluminium rings to contain the sand. The thin gaps between the plywood strips were covered by overlapped spring steel strips. The side walls were covered internally by a thin, silicone lubricated latex rubber sheet. The end walls and base of the stack were coated with sand, which was bonded with glue. The measured natural frequency of the empty shear stack was 3.5Hz. When full of sand, the shear stack weighed approximately 10 tonnes.

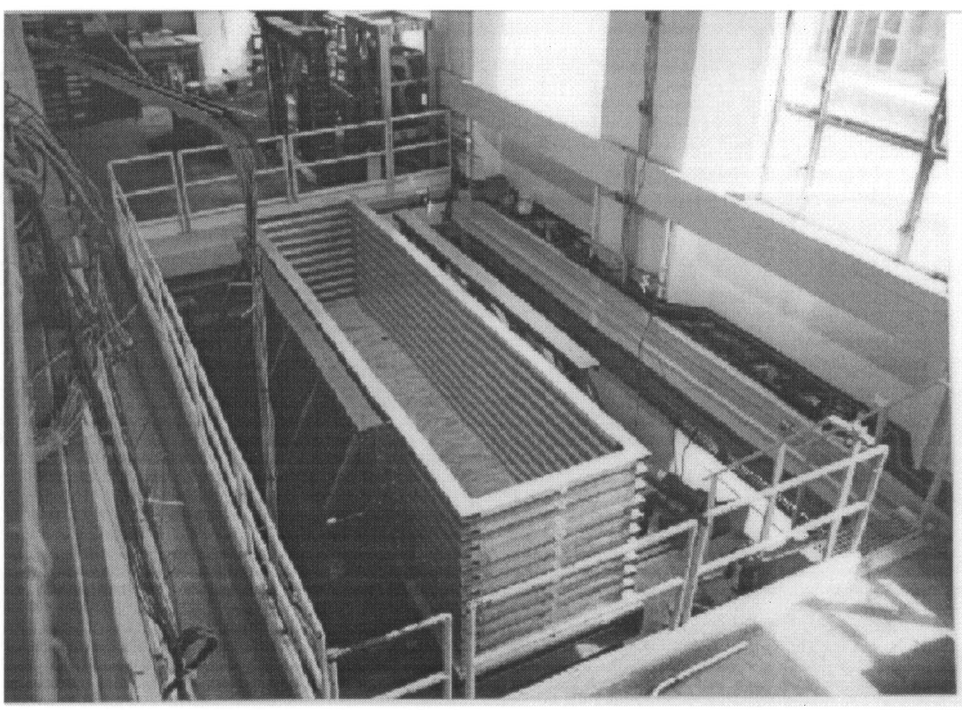

Fig. 2 Empty shear stack on the shaking table.

DEVELOPMENT TESTS

Two series of development tests were performed. The first was to assess the performance of the new shear stack in comparison with the earlier version and used a dry dense sand sample with no foundation block.

This represented a "free field" case. The second used a medium density dry sand sample supporting a simple direct footing.

The sand selected was a fairly coarse 14/25 Leighton Buzzard sand for which there is a high quality simple shear test database produced by Stroud (1971) and Budhu (1979). The sand has a ϕ_{cv} of approximately 33°. For the free-field tests, the sand deposit was placed in 100 mm layers, each being shaken down after placing. This produced a very dense sample with a relative density in excess of 90%. In the foundation tests a looser sample was created by drawing a perforated steel sheet through each layer as it was placed then, when the stack was full, it was shaken with random motions to compact it to a relative density of 58%. A sand spreader will be used to prepare uniform samples of relative density between 60-70% in subsequent tests.

Free-field tests with a dense sample

The empty and filled shear stack was tested first with low level random noise inputs to measure the system resonant frequencies. Then the filled stack was shaken with a series of horizontal 10Hz sine dwell motions with gradually increasing amplitude. The dwells comprised a 10 cycle ramp up, 20 cycle dwell at constant amplitude and a 10 cycle ramp down. In some cases, two sine dwells of different amplitudes were used end-on, separated by a lower amplitude dwell period (e.g. Fig. 3(a)). Accelerometers were placed on the end walls and embedded in the sample. Displacement transducers were arranged to measure the vertical and horizontal displacements of a perspex plate embedded in the surface of the sand.

Under low level random excitations, with a RMS acceleration of 0.05g, the filled stack had a natural frequency of about 31.5Hz, indicating that the soil specimen had an average shear wave velocity of approximately 150m/s. Modal measurements indicated that the lateral displacements followed the expected sinusoidal profile. Further tests would evaluate the uniformity of accelerations over horizontal planes, but initial results show good coupling between the soils and stack responses.

Taylor, Dar and Crewe (1994) showed that the sand in the small shear stack failed when certain critical table accelerations were reached. Strong dilation of the sand was associated with this failure, causing the surface to rise by several millimetres. Coloured vertical bands placed in the sand showed that failure occurred on narrow horizontal planes, about 10mm thick, where the dilation appeared to be concentrated. The planes were about 200mm from the surface and a similar distance from the base of the stack. A series of sine dwell tests were conducted on the new shear stack to try to replicate this behaviour.

Figs. 3(b-c) show the horizontal and vertical surface responses respectively for a particularly strong input motion which had a peak horizontal table acceleration of 0.63g (Fig. 3(a)). The surface started to rise as the table acceleration reached about 0.3g and continued to do so as the acceleration amplitude in the first ramp-up of the dwell increased to the peak value of 0.63g. During the subsequent 20 cycle dwell at this amplitude, the surface began to settle by a total of about 1.5mm. The measured surface behaviour of large shear stack sample was the similar to that for the small shear stack.

After 20 cycles the table acceleration was reduced to about 0.4g, thereby reducing the amplitude of the cyclic shear stresses in the specimen and pulling the stresses on the failure plane away from the stress failure envelope. At this stage, the soil was no longer failing and the dilation ceased, this being reflected by the constant surface displacement during this period. When the accelerations increased again, dilation started almost immediately, rising to a peak surface displacement of about 2.7mm. This time, the mean surface displacement remained constant during the third dwell period. Gradual shaking down occurred as the table motions tapered to zero. The higher frequency oscillations superimposed on the mean surface displacements were at the same frequency (10Hz) as the input motions. It is believed these represented the rolling of sand grains backwards and forwards over each other, which is consistent with behaviour in the simple shear apparatus observed by Budhu (1979). The above behaviour was entirely consistent with the previous small shear stack.

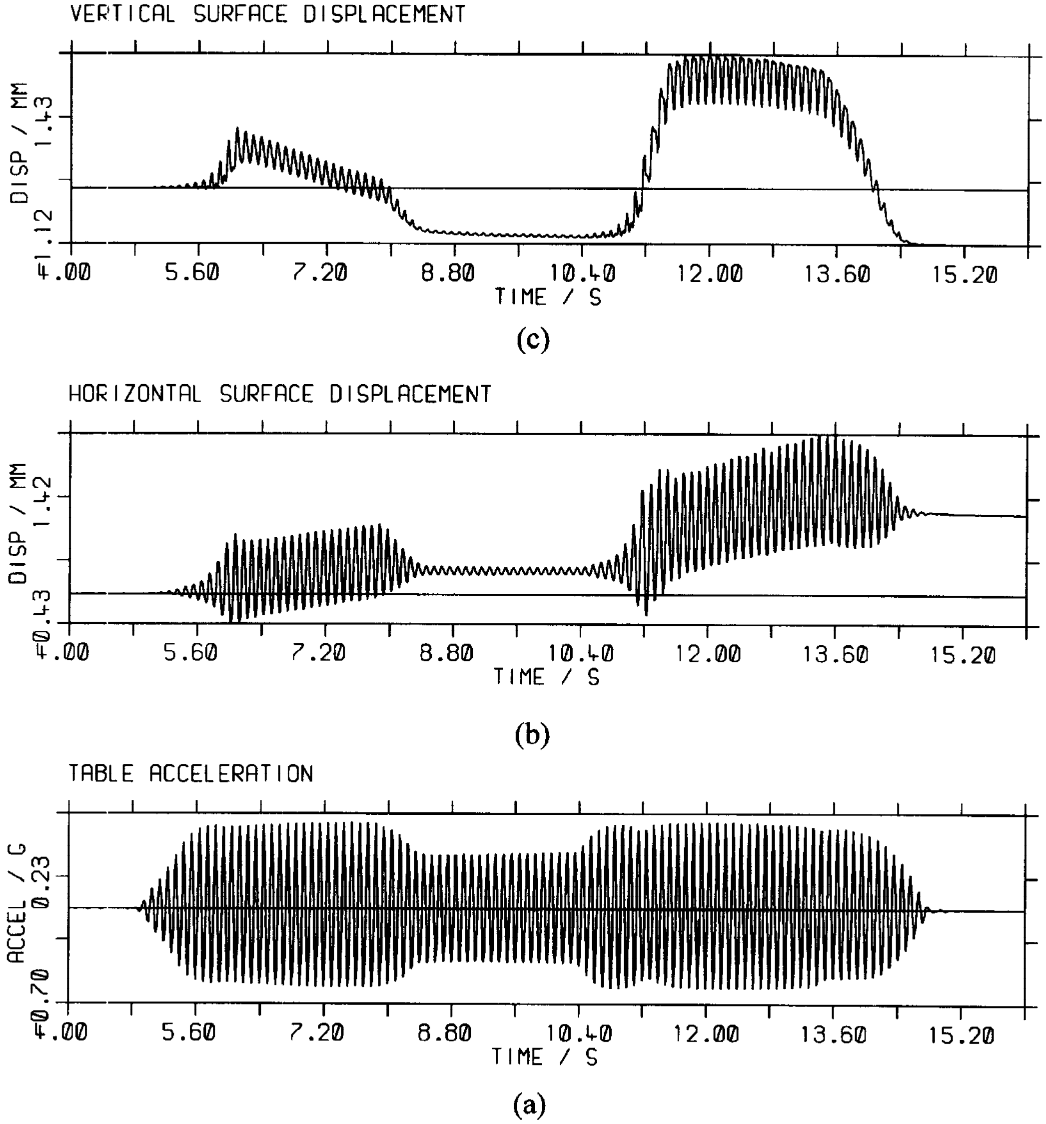

Fig. 3. Free-field surface response to sine dwell input

Foundation tests

The foundation tests used a 0.4m wide by 0.4m high concrete foundation block spanning the full width of the shear stack. The block was embedded by 0.1m. Three tonnes of steel kentledge was placed on the foundation, giving a vertical bearing pressure of 85KPa. The centre of gravity of the kentledge was about 0.6m above the sand surface. Input motions were based on an acceleration time history measured at Gemona during the 1976 Friuli, Italy earthquake. The input was applied as a single, in-plane horizontal component compressed in time by a factor of ten. Accelerations were measured in the soil, and on the foundation and shear stack. Foundation displacements were recorded, as were direct normal stresses on the foundation base and in the base, side and end walls of the shear stack. The aims of the tests were to provide an initial characterisation of the mode of failure of the foundation and provide a database for comparison with numerical models and for designing a more detailed series of tests.

Prior to the seismic tests, the transmissibility functions were measured between the table acceleration and the response accelerations measured on the sand surface and on the foundation block, respectively. Broad band (0-100Hz) random vibrations were applied, having an RMS amplitude of 0.05g. At this level of excitation, the responses of the soil deposit and foundation were essentially elastic. The 'free-field' transmissibility, measured on the sand surface 1.2m away from the foundation block, gave a dominant response frequency of 36.5Hz with a damping factor of 3.5%. The foundation block transmissibility gave a frequency of 5.4Hz and a damping factor of 16.4%.

For the main seismic test, a series of ten shakes was applied, with peak table accelerations increasing incrementally from 0.44g to 1.5g. Fig. 4 shows the final displacements and rotation of the foundation block after each shake plotted against the peak table acceleration. The block settled gradually during the shakes up to 1.23g peak table acceleration, whereupon the rotation became more pronounced, reaching a maximum of about 5° after the penultimate shake. For the final shake, the input motion was reversed, but the block rotated in the same direction as previously until it engaged with a safety restraint. After the tests, the deposit was excavated carefully and it was noted that the embedded accelerometers had displaced and rotated in a manner broadly consistent with the development of a curved rupture zone, although no detailed measurements were possible.

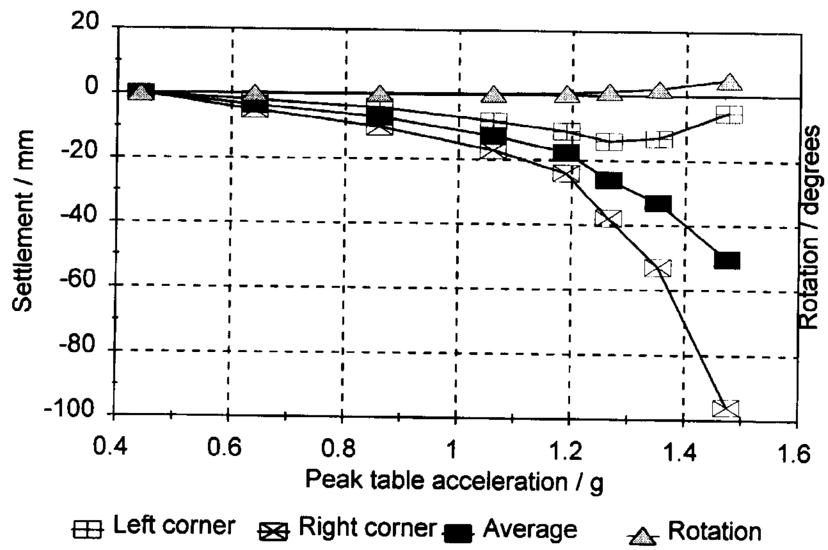

Fig. 4. Displacements of foundation block

Fig. 5 shows selected time history responses for the shake at which the foundation rotation became pronounced. The horizontal foundation accelerations were measured at the top of the kentledge, approximately 450mm above the top of the concrete foundation block, and at the bottom of the kentledge slightly above the concrete block. The settlements were measured at the bottom corners of the kentledge, 1000mm apart. It is clear from Fig. 5 that the right corner gradually penetrated into the sand, while the left corner showed relatively small settlements. The peak accelerations of the foundation block were somewhat lower than the shaking table accelerations. This may have been due to the onset of sliding of the foundation on a failure surface. Further tests will explore this factor.

CONCLUSIONS

A large flexible shear stack has been developed for testing small direct foundations at prototype scales on a shaking table. The performance of the shear stack has been shown to be good, replicating free field boundary conditions in a reasonable manner. The initial foundation and free field experiments have yielded useful insights into the failure of simple direct foundation founded on dry sand. Quantitative data have been collected that will be of value in subsequent numerical model validation.

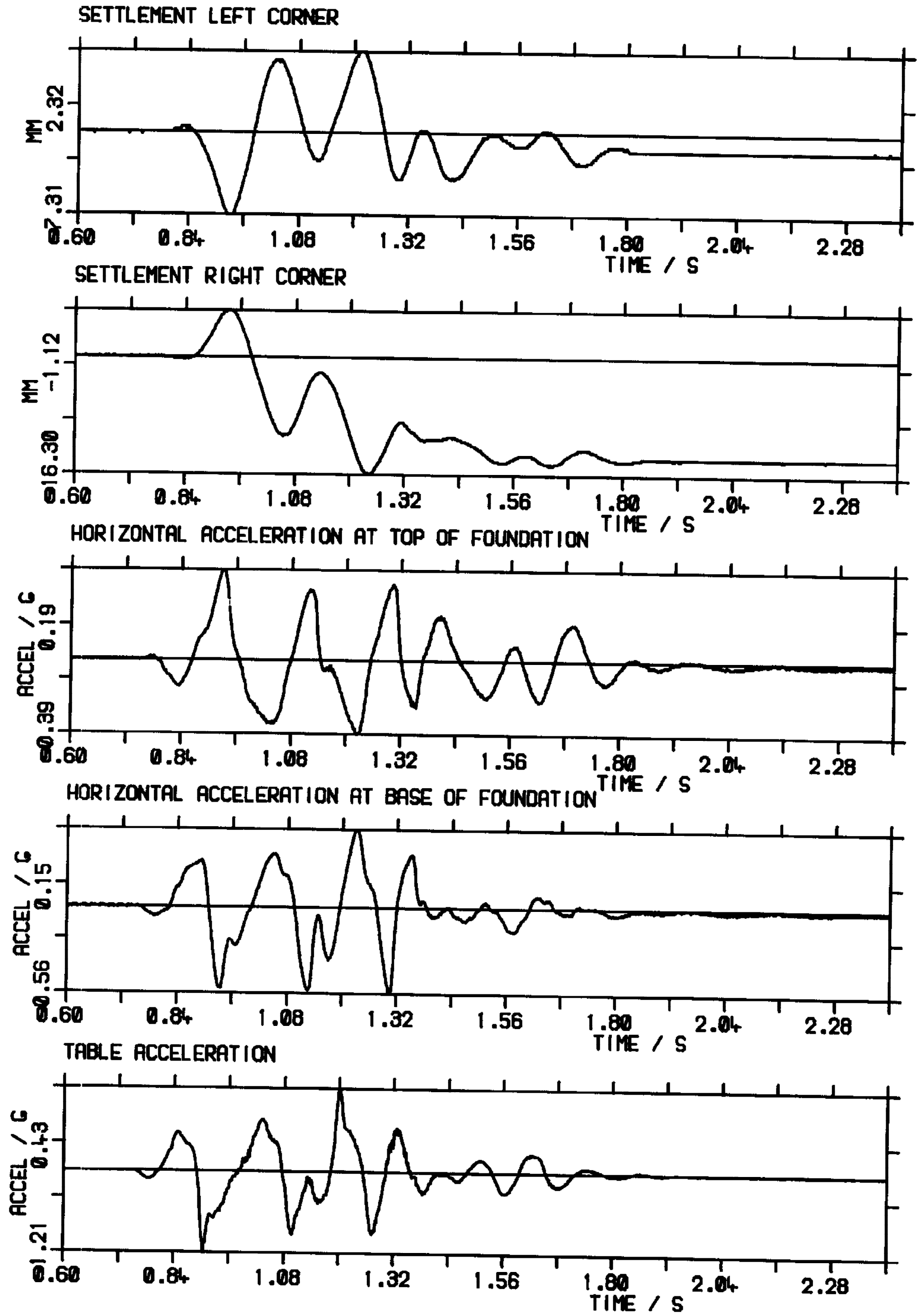

Fig. 5. Response of foundation block to a 1.23g peak table acceleration shake

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