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A predictive exercise on the behaviour of tunnels under seismic actions

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ABSTRACT: The calibration of numerical procedures for the prediction in design of the behaviour of tunnels under seismic conditions should be validated against experimental data. Centrifuge tests were carried out at the University of Cambridge (UK) on tunnel models in sand, for the assessment of different analytical methods developed in the framework of Italian ReLUIS-DPC Project. After the end of the research project, the experimental data have been made available online to the scientific community to be used for benchmarking simplified to complex dynamic numerical methods. This paper describes the organization of such a predictive exercise, promoted by TC204 together with TC104 and TC203 of ISSMGE.

1 INTRODUCTION

The behaviour of urban tunnels under seismic actions can be predicted by simplified (based on the pseudo-static approach) and dynamic methods, i.e. more complex procedures that take into account the dynamic nature of the seismic loads and the cyclic soil behaviour. These latter methods can either uncouple the analysis of free-field soil response from that of the tunnel ('*simplified dynamic analysis*'), or use complex numerical procedures (*full dynamic analysis*) accounting for soil-structure interaction, which is basically kinematic (*cfr.* Owen & Scholl, 1981; JSCE, 1992; AFPS/AFTES Guidelines, 2001; ISO TC 98, 2003; AGI, 2005). The calibration of all such methods should require validation against experimental data, which are seldom available at the prototype scale: centrifuge modelling is therefore an alternative powerful tool to produce 'artificial case histories' for calibration, back-analysis or benchmarking between different analytical approaches.

Centrifuge tests were carried out by researchers of the University of Napoli Federico II at the Schofield Centre of the University of Cambridge (UK) on tunnel models in sand (Lanzano, 2009), for the assessment of different analytical methods developed in the framework of ReLUIS Project 2005–2009 (Bilotta et al. 2007 and 2008). After the end of the research project, the experimental data can now be made available to the scientific community.

The experimental activity will be briefly described in this paper, further details can be found in referenced papers (Bilotta et al, 2009, Lanzano et al, 2009, Lanzano et al. 2010).

2 BACKGROUND

A systematic collection of data concerning damages to underground structures and tunnels after seimic events was carried out only after the San Fernando earthquake in 1971 ($M_w = 6.6$). In 1974 the American Society of Civil Engineers published some data about the damage to underground structures in the Los Angeles area following that event. Later the database of observed damages grew up in the years, mainly with data from cases occurred during earthquakes in the United States and in Japan (*cfr* Dowding & Rozen, 1978; Owen & Scholl, 1981; Sharma & Judd, 1991; Power et al., 1996; Lanzano et al., 2008).

A typical damage pattern due to the longitudinal and transversal components of ground motion is that of extension cracks along the tunnel lining. In the transverse section of a circular tunnel, for instance, the ground shaking induces ovalisation of the lining (Owen & Scholl, 1981). Hence, depending on the stress level of the lining under 'static' conditions, cracks may open where tensile stress increments arise during shaking (Fig.1).

Although it is quite difficult to measure such increments of internal forces during real earthquakes, centrifuge modelling allowed an experimental assessment of these quantities during 'artificial seismic events'; the results may be used for benchmarking simplified to complex prediction methods.

3 CENTRIFUGE TESTING PROGRAMME

Four centrifuge tests were carried out on tunnel models in dry sand at two different values of relative density, in a laminar box ($500 \times 250 \times 300$ mm^3).

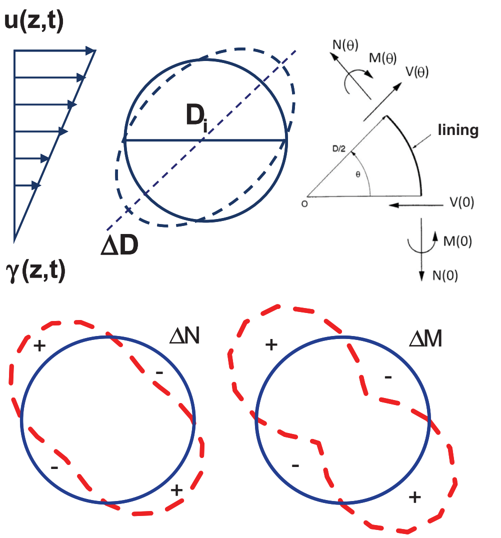

Figure 1. Typical increase of the lining internal forces due to ground shaking in the transverse section of a tunnel.

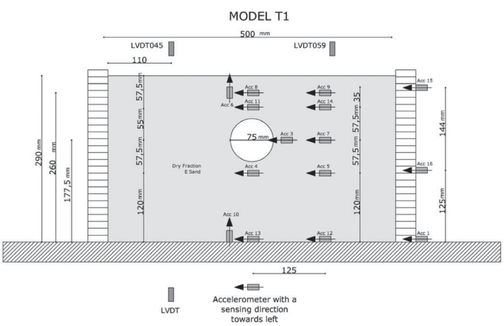

Figure 2. Schematic setup of model T1.

Table 1. Centrifuge tunnel tests.

Model	D (mm)	C (mm)	D_r	N
T1	75	75	~80%	80
T2	75	75	~40%	80
T3	75	150	~80%	80
T4	75	150	~40%	80

A schematic setup is shown in Fig. 2. The testing programme is summarized in Table 1 (model scale), where D is the diameter of the tunnel, C is the cover, D_r is the relative density of the sand and N is the g-level (Lanzano and Madabhushi, 2007a, b).

4 FACILITIES

4.1 *Philip Turner centrifuge*

The centrifuge tests at Schofield centre were carried out in a 10 m beam centrifuge, named from the engineer, P.W. Turner, who designed this facility in the early 1970's (Schofield, 1980).

The centrifuge consists essentially of a beam-like structure, which rotates about a central vertical axis. Dynamic tests can be carried out at centrifuge acceleration in the range of 40 to 100 g. In the performed tests, a swinging platform carrying the model and the dynamic SAM actuator was installed on one end of the beam and the required counterweight was placed on the other end.

4.2 *SAM actuator*

The Stored Angular Momentum (SAM) is an earthquake actuator developed at Cambridge University (Madabhushi et al.1998). The SAM actuator is a powerful tool and allows simulating strong earthquakes at high acceleration level; it can fire series of earthquakes at different frequencies, duration and g-level.

Very high levels of energy can be stored in a fly wheel spinning at high angular velocities. The energy stored in the fly wheel may be used to subject the centrifuge model to earthquakes. The angular velocity of the fly wheel determines the frequency of the earthquake. The duration of the earthquake is controlled by a fast acting clutch which starts and ends the earthquake. The strength of the earthquake can be controlled by altering the pivot point of the lever.

The soil model is shaken in the direction of centrifuge flight and the fly wheel rotates in the plane of rotation of the centrifuge arms. The variables that can be changed during the tests are:

- the level of inertial acceleration 'g';
- the frequency of the signal;
- the amplitude of the signal;
- the duration of the signal.

4.3 *Laminar Box (LB)*

The tests were performed using a Laminar Box (Fig. 3). This box is made by a series of stacked rectangular frames which can slip reciprocally through ball bearings. This solution is useful to minimize the friction between the laminae and to allow the horizontal movements of the whole box. The model container has inner sizes of $500 \times 250 \times 200$ mm^3 and a mass of 93.5 kg.

A plate is put at the base of the box to connect the container with the SAM actuator so to fire the earthquake on the model. The weight of the plate is 58 kg.

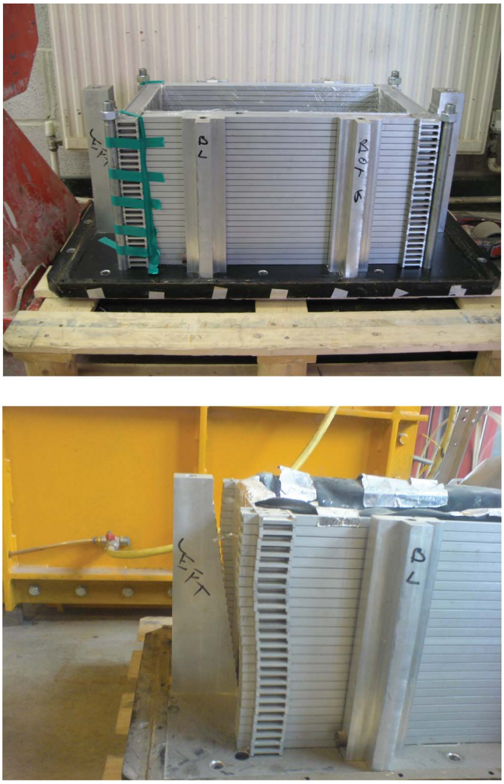

Figure 3. Undeformed (above) and deformed (below) Laminar Box.

5 MATERIALS

5.1 *Sand—Leighton Buzzard*

All the models were made using dry Leighton Buzzard sand (grade E) reconstituted at two different relative densities Dr (about 50% and 80%). The specific gravity of the sand is 2.65 and the maximum and minimum void ratios are 1.014 and 0.613 respectively (Jeytharan, 1991). A detailed characterization of the sand used in tests was performed in laboratory by means of triaxial and resonant column tests at the University of Napoli Federico II (Visone, 2009).

5.2 *Alloy (Dural)*

The tunnel lining was modelled using an aluminium tube having an external diameter D = 75 mm and a thickness t = 0.5 mm. The unit weight of aluminium is 2770 kg/m^3. At N = 80 g, the model would correspond to a 6 m diameter prototype tunnel with a shotcrete lining of about 6 cm.

6 INSTRUMENTATION

6.1 *Accelerometers*

Miniature piezoelectric accelerometers manufactured by D.J. Birchall Ltd™ were used to measure horizontal and vertical acceleration in the soil and on the model container during earthquakes (see Fig. 2). The device has a resonant frequency of about 50 kHz and maximum error of 5%; the transducer weight is about 5 grams.

6.2 *Strain gauges*

The tube has been instrumented in order to measure bending moments (BM) and hoop forces (HS) at 4 locations along 2 transverse sections (Figs. 4 & 5).

The main instrumented section was located at the mid-span of the tube and a second section 50 mm aside. This second section was needed for two reasons: checking the plane strain behaviour of the tunnel model (BM and HS at corresponding locations of

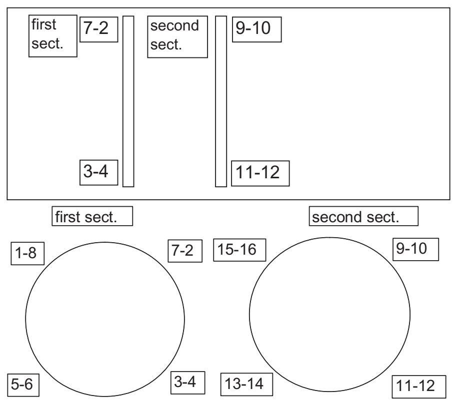

Figure 4. Strain gauges position.

Figure 5. Instrumented tube.

different sections should be the same) and for redundancy of experimental data. In total 16 Wheatstone bridges (4 locations × 2 sections × 2 force measurements) were glued to the tube and wired.

6.3 *Displacement measuring device (LVDTs)*

The vertical displacement of the surface during centrifuge tests was measured by linear variable differential transformers (LVDTs) manufactured by Sangamo™. Each transducer weighs about 36 grams. LVDTs were placed in two gantries above the model.

7 INSTRUMENTATION

7.1 *Container preparation*

The Laminar Box was initially cleaned from the remains of previous test. At this stage the container was blocked with four columns at the corners of the box to prevent the movements during the model preparation, transportation and assembly. A grease layer was interposed between the box and an internal rubber lining. The internal rubber was stretched and was fixed at the box top by aluminium tape. The sockets for the external accelerometers were glued on the lateral surface of the box. A paper ruler was stuck on the internal wall to control the level of the sand during the pouring phase. Before pouring the sand, the external walls of the box were protected by black plastic liners that were removed at the end of the deposition: this was to avoid that sand grains could accidentally enter between the laminae.

7.2 *Sand pouring*

To make the "loose sand models", the sand was poured into the strongbox through a simple hopper system. The void ratio was therefore dependent on the height of the hopper and the opening of the slot at the bottom that controlled the rate of flow of the sand. A few trial tests were performed in advance to calibrate these values. After that the required height of the sand layer was achieved, the surface of the sand was levelled by a modified vacuum cleaner.

To make the "dense sand models", the sand was poured into the strongbox through an automatic hopper system which adopted a multiple sieving pluviation technique (Miura & Toki, 1982). The pouring of the sand was controlled by a computer. The parameters that played a crucial role in order to obtain the desired density were the height of fall and the nozzle diameter. During each pluviation step the sand was poured first longitudinally and then transversally with an offset of 15 mm. At the end of the step the hopper was lifted up by 10 mm (the height corresponding to the thickness of the layer poured in each step). During the sand deposition the instruments and the model tunnel were positioned in the model.

7.3 *Accelerometers positioning*

Before each test a layout drawing of the model was prepared, where the position and the sensing direction of every accelerometer was shown, such as in the example shown in Fig. 2. The accelerometers were placed in the model (Fig. 6) according to the indications of the layout. A vertical array of three accelerometers was deployed laterally to the laminar box, including one at the bottom identifying the 'bedrock reference motion'.

7.4 *Tunnel placement*

Once the level of the sand in the container reached the level of the tunnel invert, the instrumented tube was placed in the model (Fig. 7) according to the test layout (see Fig. 2). As the tunnel tube is shorter

Figure 6. Accelerometers positioning.

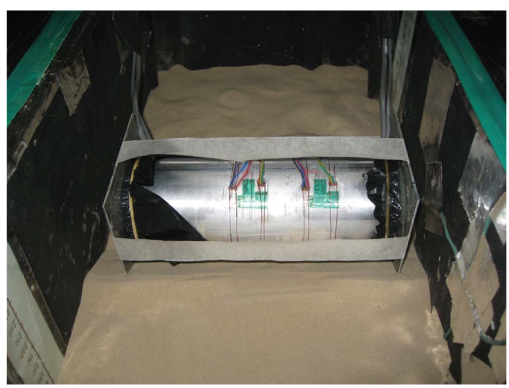

Figure 7. Tunnel placement.

than the box width by 50 mm (to avoid interaction with the container during shaking), two square plates were also placed at each end of the tunnel to avoid loss of sand inside the tube during the test. To reduce friction between the plates and the tube, the plates were lubricated and a black plastic liner patch was inserted in between.

8 TEST PROCEDURE

Before starting the centrifuge flight, the corner columns were removed. When the test started the centrifuge was swung up in steps of 10 g, from 10 g to 80 g. At each stage the readings of strain gauges transducers were recorded. Then the first earthquake was fired. After 4 earthquakes at 80 g, the centrifuge was slowed down at 40 g to fire another earthquake. Then the centrifuge was swung down. The model was permanently monitored through a camera installed on the beam.

9 TEST DATA

The channels for the measurements were 32 in all: 16 for the accelerometers and 16 for strain gauges or LVDTs. The data were plotted out channel by channel and recorded in a text file both for the swing up phase and every earthquake. All the data were acquired using the software CDAQS (Centrifuge Data AcQuisition System), a system that minimizes the noise derived by electrical interference of the SAM actuator. The earthquake data were sampled at a rate of 4 kHz. A typical set of records is shown in Fig. 8.

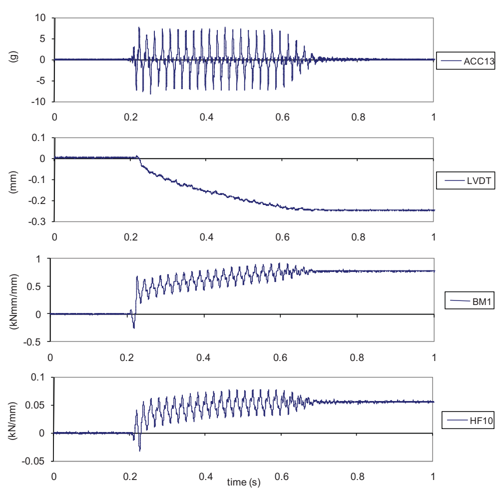

Figure 8. Typical outputs of an accelerometer, a LVDT, a BM and a HS strain gauges during T1 test (EQ3).

10 BENCHMARK TEST T3

The test initially selected for the benchmark, T3, is a model of dense sand and deep tunnel, the layout of which is drawn in Fig. 9. The internal available volume of the box (without the volume of the tunnel) is 3.32*107 mm^3 and the mass of the used sand is 51.5 kg. These values give a void ratio of 0.710 and a relative density of 75.9%. A total of 31 transducers were used in this test: 16 accelerometers, 13 strain gauges and 2 LVDTs. Four earthquakes were fired at 80 g and one at 40 g, with variable nominal peak acceleration amplitude and frequency. The main features of each earthquake are shown in Table 2, at the model and prototype (bracketed values) scales; their time histories, as recorded by the reference accelerometer Acc13, are resumed in Fig. 10.

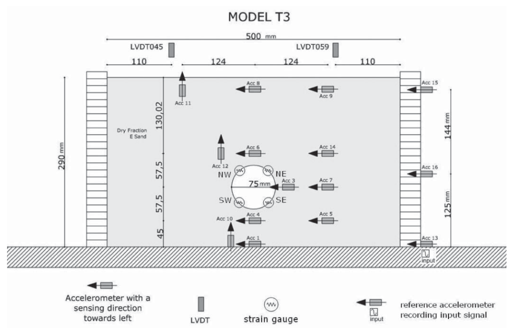

Figure 9. Layout of the model T3.

Table 2. Earthquakes fired in test T3.

Earthquake #	N	Frequency (Hz)	Duration (s)	Nominal PGA (g)
1	80	30 [0.375]	0.4 [32]	4 [0.05]
2	80	40 [0.5]	0.4 [32]	8 [0.10]
3	80	50 [0.625]	0.4 [32]	9.6 [0.12]
4	80	60 [0. 75]	0.4 [32]	12 [0.15]
5	40	50 [1.25]	0.4 [16]	12 [0.30]

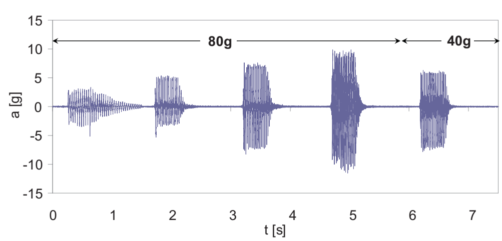

Figure 10. Time histories of input signals recorded by Acc13.

11 ROUND ROBIN TUNNEL TEST ORGANIZATION

The Round Robin Tunnel Test (RRTT) is jointly promoted by three ISSMGE Technical Committees, i.e. TC104 (*Physical modelling in Geotechnics*), TC203 (*Earthquake Geotechnical Engineering*) and TC204 (*Underground construction in soft ground*). Both researchers and practitioners are welcome to participate by writing to the Authors (emilio.bilotta@unina.it, francesco.silvestri@unina.it).

All participants will be enabled to use the selected test data, i.e. the reference accelerograms (Fig. 10) and the results of laboratory tests on LB sand, which are delivered through ftp with a restricted access. The analyses will be intended as 'blind' predictions.

Each participant will specify: (i) people involved and expected time of accomplishment (no. of months), (ii) the types of analyses which will be carried out (approach, numerical code, constitutive model, prototype or model scale), (iii) the output data to be benchmarked (e.g. acceleration amplitudes, soil strains, surface settlements, load increments in the lining), (iv) the will of participate to periodic meetings to be scheduled on purpose and/or during next international symposia related to tunnels and geotechnical earthquake engineering.

At his point they will receive a ftp address together with username and password to download the required input data and to upload the output data at the end of the analyses. Upon delivering the numerical output data, they will receive the corresponding experimental values to be taken as a reference for the benchmarking.

Finally, each attendant also will submit to the organizers a synthetic report with details on the numerical procedure and comparisons between numerical and experimental data. The reports may be collected in a short volume, jointly edited by TC203 and TC204. In the meantime, the participants will also be free to publish, either individually or through jointed co-operation with other groups subscribing the RRTT, any comparison between numerical and experimental data, provided the data source be properly quoted.

ACKNOWLEDGEMENTS

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