CENTRIFUGE TESTING ON FLEXIBLE CIRCULAR TUNNELS

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ABSTRACT: The seismic safety of the underground structures is an important subject related to many civil engineering projects. The behaviour of the flexible, shallow tunnels under earthquake loading is not understood completely. This paper presents the initial results of shaking table and centrifuge experiments conducted on shallow, flexible tunnels. The results suggest that the confinement pressure plays a major role in the safety of the flexible, shallow, circular tunnels.

Keywords: Tunnels; Earthquake; Seismic Behaviour; Underground Structures;

1. INTRODUCTION

The safety of the underground structures in seismic areas is an important part of the urban transport projects in developing countries. The knowledge available regarding the behaviour of tunnels in soft ground during an earthquake loading is limited. Current design approaches rely either on analytical methods which are based on elasticity theories or on complex numerical analyses to simulate dynamic behaviour of the tunnels. There are uncertainties regarding the soil-structure interaction of tunnel lining and the surrounding medium. Recent events such as Kobe Earthquake in Japan (1995), Duzce Earthquake in Turkey (1999), Chi-chi Earthquake in Taiwan (1999) and Bam Earthquake in Iran (2003) revealed that the poor design of underground structures may even cost lives.

There are several factors which affect the behaviour of tunnels under earthquake loading such as depth of the tunnel below the ground surface, the type of soil or rock surrounding the tunnel, the maximum ground acceleration, the intensity of the earthquake, the distance to the earthquake epicenter and the type of tunnel lining affect the behaviour of the tunnels under earthquake loading. The relative effects of these factors are unknown but reported cases state that underground structures suffer less damage than the surface structures, the damage decreases with overburden depth and the duration of the earthquake plays an important role due to its effect on lining fatigue. Case studies showed that the accelerations amplified upon incidence onto a tunnel, if the wavelengths are between one and four times the tunnel diameter. Peak ground acceleration and velocity or fault movements can be related to the damage received by the tunnel structure. The slope-stability at or near tunnel portals, floatation and sinking of the tunnel due to liquefaction are amajor causes of reported damage in the tunnels [1, 2, 3].

Current analytical methods which are based on elasticity theory ignore the effects of inertia. Free-field approaches assume that the strains in the tunnel structure and the free-field strains are the same [4]. Some other methods use strain compatibility functions which relates the deformation of the lining with the free field deformations [1, 2, 5, 6, 7]. Daikai station of the Kobe subway system, which was designed using this methodology, has collapsed in 1995 Kobe earthquake [8].

Among other design methods are the dynamic earth pressure models like the commonly used Mononobe-Okabe method developed for retaining walls and the dynamic soil-structure interaction analyses. Dynamic soil structure analyses are generally complex if the inelastic effects are taken into account and there is a need for experimental verification.

This paper is focused on the results of dynamic centrifuge tests carried on flexible circular tunnels in soft sand. The behaviour of the circular tunnel is compared both to the green field behaviour (control test without tunnel) and to the complimentary shaking table test under 1g.

2. EXPERIMENTAL SETUP

2.1. Centrifuge Modelling

The purpose of geotechnical centrifuge modelling in this research is to test small scale circular tunnel model subjected to acceleration fields of magnitude many times Earth's gravity in order to obtain the stress-strain conditions at homologous points of the scaled-down model and large scale prototype being the same. The experiments were carried on using the 10m diameter beam centrifuge in Schofield Centre for Geotechnical Process and Construction Modelling (SCC) at the University of Cambridge. The capacity of the beam centrifuge is 150g-tonnes. It is capable of accelerating 1 tonne of load up to 150g (rotational speed of 186 rpm). Two tests were carried on under 50g of centrifugal acceleration. First test was a control test without any tunnel in the model. In the second test a circular tunnel of 100mm diameter (5m in prototype scale) is used. It was made of 0.25 mm thick aluminium (12.5 mm in prototype) and was 235mm long. The depth of soil was 280 mm (14 m in prototype) for both the control test and the tunnel model test. The embedment depth of the tunnel was 50mm (2.5 m in prototype) as shown in figure 2.

The Stored Angular Momentum (SAM) actuator is used to obtain lateral shaking in the dynamic centrifuge tests (Fig. 3). A powerful earthquake actuator is necessary for the dynamic centrifuge experiments due to the need of high frequency shaking in very short time intervals. This is achieved by storing the angular momentum in a pair of spinning flywheels which are rotated reciprocally by means of a conventional electric motor.

A bell crank mechanism with a variable lever arm length converts the reciprocating motion of the flywheels to lateral shaking after a fast-acting hydraulic clutch releases the energy stored in the flywheels to the package. More information on the SAM Actuator is given by Madabhushi et al. [9].

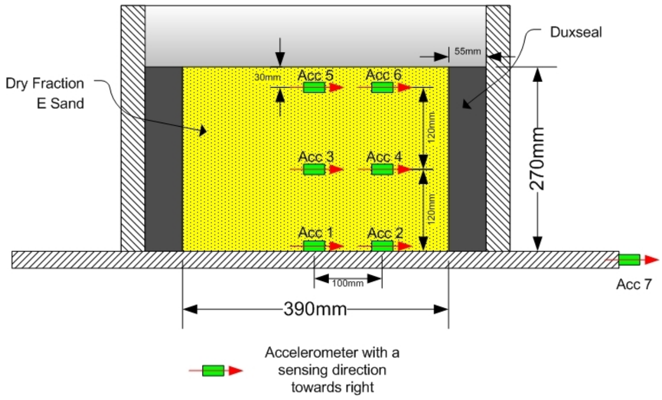

Fig. 1. Model layouts for UC-01 control test

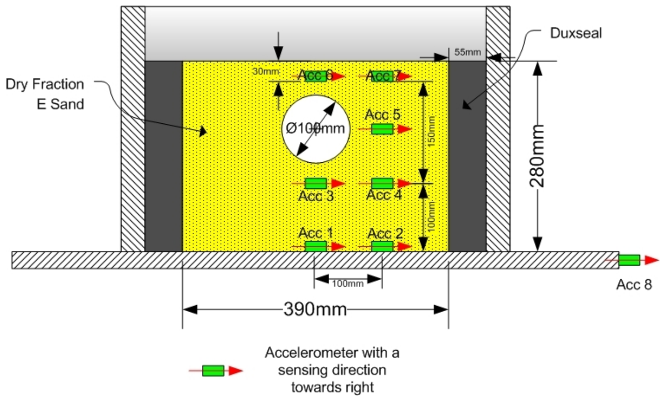

Fig. 2. Model layouts for UC-02 dynamic centrifuge test for the circular tunnel

Fig.3. SAM actuator

The model was prepared inside an aluminium model box which has internal dimensions of 500mm long by 235mm wide and 300mm deep as shown in figure 1 and 2. The box has a perspex viewing window which enables the deformations of the tunnel structure and of the soil around the tunnel to be observed. A fast camera capable of recording digital images at 1000 frames/second is used to capture the deformations inside the model. Due to the space limitations, the camera and the light were placed in a vertical position above the window box and a mirror is mounted on the window box at an angle of 45° in order to get a view of the perspex window. A gauntry to carry camera and the light was designed for this purpose and mounted on the swing (See figure 4).

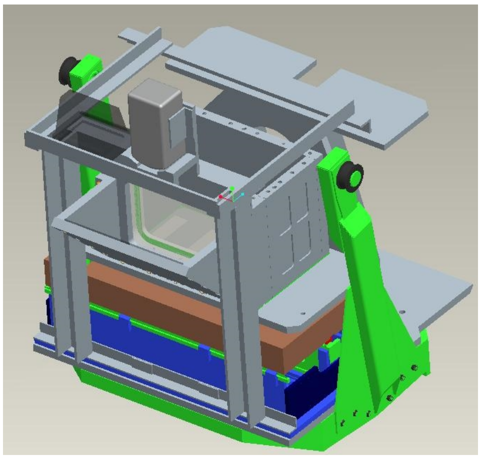

Fig.4. Window box on the swing

Free field behaviour of the soil cannot be simulated properly in a rigid box [10]. Therefore two vertical layers of duxseal having a thickness of 55 mm were used to decrease the amount of reflection of P-waves at the ends of the rigid box [11].

For circular tunnels, the flexural stiffness of the medium relative to the tunnel lining is given by the flexibility ratio F, which is expressed as [12]:

$$F = \frac{E_m\left(1-\nu_l^2\right)R^3}{6E_l I(1+\nu_m)} \qquad (1)$$

where E_m is the modulus of elasticity of the medium, E_l is the modulus of elasticity of the tunnel lining, I is the moment of inertia of the lining (per unit width) for circular tunnel having a radius R, ν_m is the Poisson's ratio of the medium and ν_l is the Poisson's ratio of the lining. The initial modulus of elasticity of the medium can be calculated using the empirical relationship given by Hardin and Drnevich [13] for small-strain shear modulus as shown in Eq.(2).

$$G_{\max} = 100\frac{(3-e)^2}{(1+e)}(p')^{0.5} \qquad (2)$$

The modulus of elasticity can then be found using the following relationship:

$$E_m = 2G_{\max}(1+\nu_m) \qquad (3)$$

The flexibility ratio of the tunnel is calculated as 27600 which shows that the lining is very flexible compared to the surrounding medium.

The sand pouring was done using air-pluviation method. Fraction E sand was used, which has the properties listed in table 1.

The input motion characteristics of the dynamic centrifuge experiments are given in table 2.

Table 1. Properties of Fraction E sand [14]

D_{10} grain size	0.095 mm
D_{50} grain size	0.14 mm
D_{60} grain size	0.15 mm
Specific Gravity G_s	2.65
Minimum Void Ratio e_{min}	0.613
Maximum Void Ratio e_{max}	1.014
Permeability at e=0.72	0.98e-04 m/s
Angle of shearing resistance at critical state	32° (estimated value)

Table 2. Input motion characteristics of centrifuge and shaking table tests (The frequency and acceleration values are in prototype scale for the centrifuge experiments.)

Test Name	Dominant Frequency (Hz)	Maximum Input Acceleration (g)
UC-01	1.0	0.20
UC-02	1.0	0.23
SUC-01	4.9	1.37

2.2. Complimentary Shaking Table Test

Several complimentary shaking table tests had been conducted with a similar setup under 1g conditions. Their results are previously reported by Cilingir and Madabhushi [15]. One particular test was conducted on 0.25mm thick and 100mm diameter circular tunnel made out of the same aluminium material. Fraction E sand was used for the experiment. The model box has internal dimensions of 700mm long by 300mm wide and 500mm deep as shown in figure 5. Input motion characteristics for the shaking table test are given in table 2. The accelerations were measured using miniature accelerometers and the experiment was captured with the 1000 frames/second fast camera. Under 1g conditions the flexibility ratio of the tunnel is calculated as 3187. Although the tunnel has a lower relative stiffness compared to the tunnel used in the centrifuge experiment, it is still quite flexible.

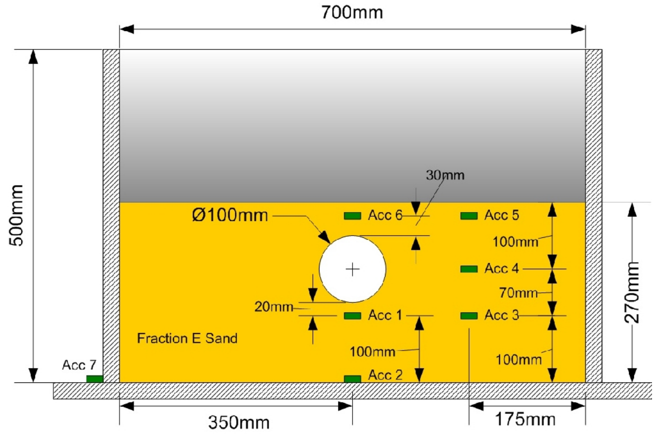

Fig.5. Layout for shaking table test SUC-01

3. EXPERIMENTAL RESULTS

3.1. Visual Observations

3.1.1. Complimentary Shaking Table Test

Visual observations revealed a strong ovaling motion of the tunnel section. There has been an accumulation of the plastic strains in the flexible tunnel lining and finally the tunnel collapsed completely. The tunnel was squeezed and then closed in the horizontal direction. Active and passive wedges were observed to be formed as shown in figure 6.

An average surface settlement of 8mm was measured. More detail about the shaking table tests is presented by Cilingir and Madabhushi [15].

3.1.2. Centrifuge Experiments

A preliminary observation from the fast camera footage showed that the tunnel lining had stood up to 50g centrifugal acceleration without any local buckling and major deformation before the earthquake.

The tunnel structure resisted a big horizontal input acceleration up to 0.19g in prototype scale although there had been some minor sand leakage into the gap formed between the tunnel face and the Perspex window at the end of the earthquake.

An average surface settlement of 10mm was measured after the earthquake.

Since the scale of the deformations in a centrifuge test is very small, further analysis is needed to detect the mode of deformation of the tunnel lining during the shaking.

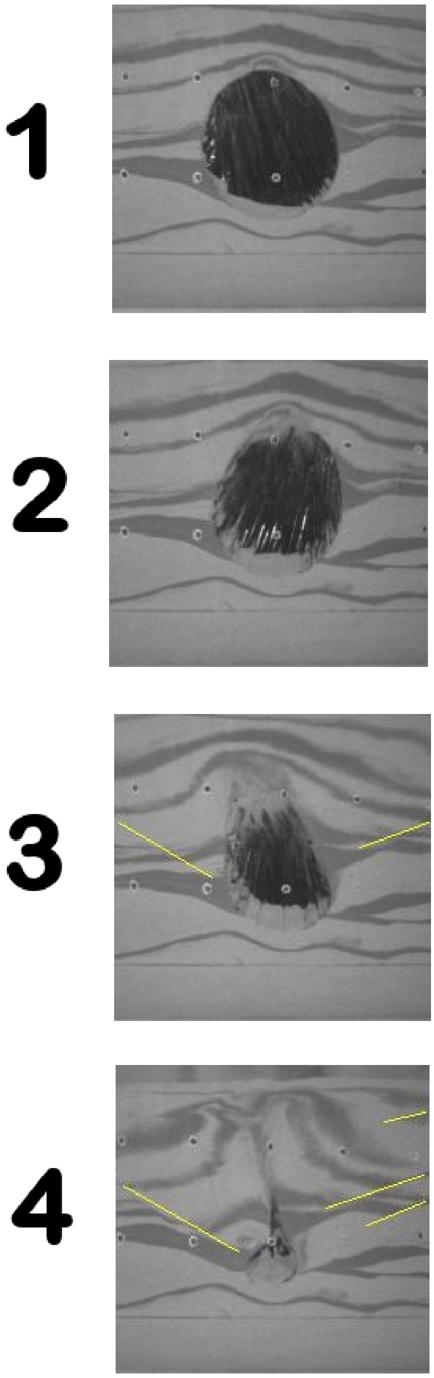

Fig.6. Progression of collapse of circular tunnel in SUC-01 (Yellow lines show the failure surfaces)

3.2. Acceleration records from centrifuge tests

The centrifuge tests showed that the accelerations were amplified both in control test UC-01 and in test UC-02. Figures 7 and 8 show acceleration time-histories for the tests UC-01 and UC-02 respectively.

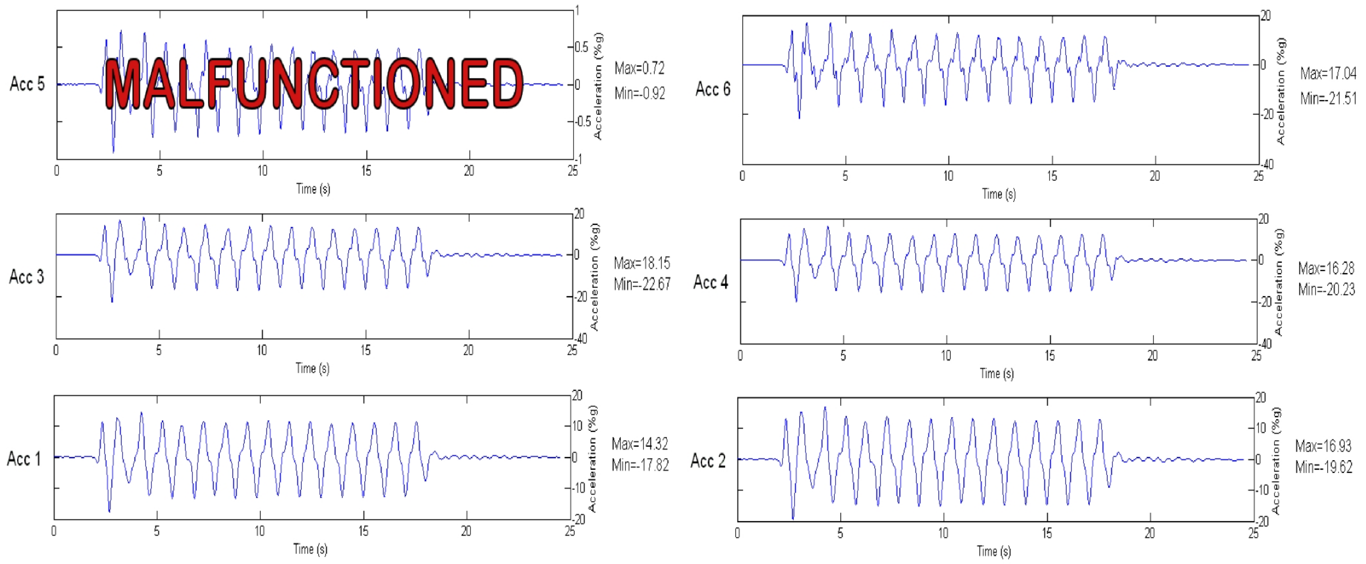

Fig.7. Acceleration time-histories from UC-01 in prototype scale. Locations of the accelerometers are shown in figure 1.

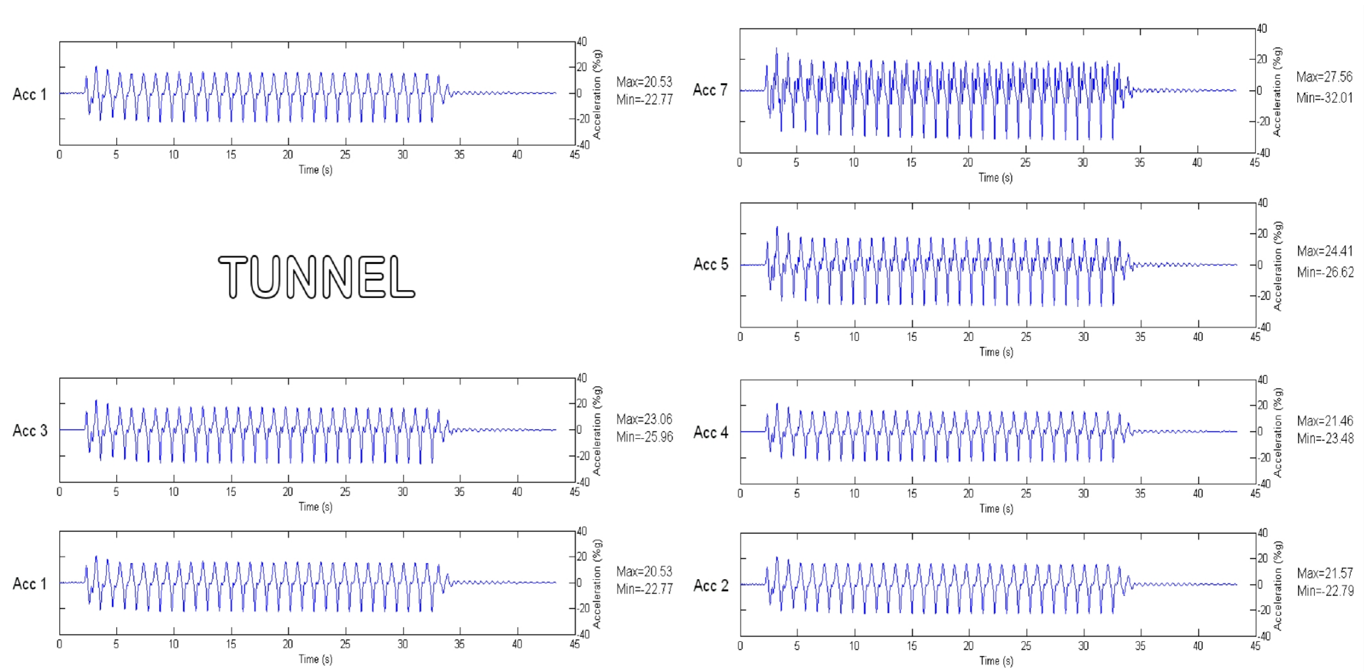

Fig.8. Acceleration time-histories from UC-02 in prototype scale. Locations of the accelerometers are shown in figure 2.

Wavelet plots were drawn in order to visualize the acceleration signals both in time and frequency space. It is a widely used analysis method for the earthquake characterization, speech recognition and image processing [16]. It is a similar method to Fourier analysis, but instead of breaking the signal into harmonic waves with different amplitudes and frequencies, it uses small wavelets with different scales. More information about this technique is given by Goupillaud et al [17] and Haigh et al [16]. Figure 9 shows wavelet plots at the base and the surface for the tests UC-01 and UC-02 respectively.

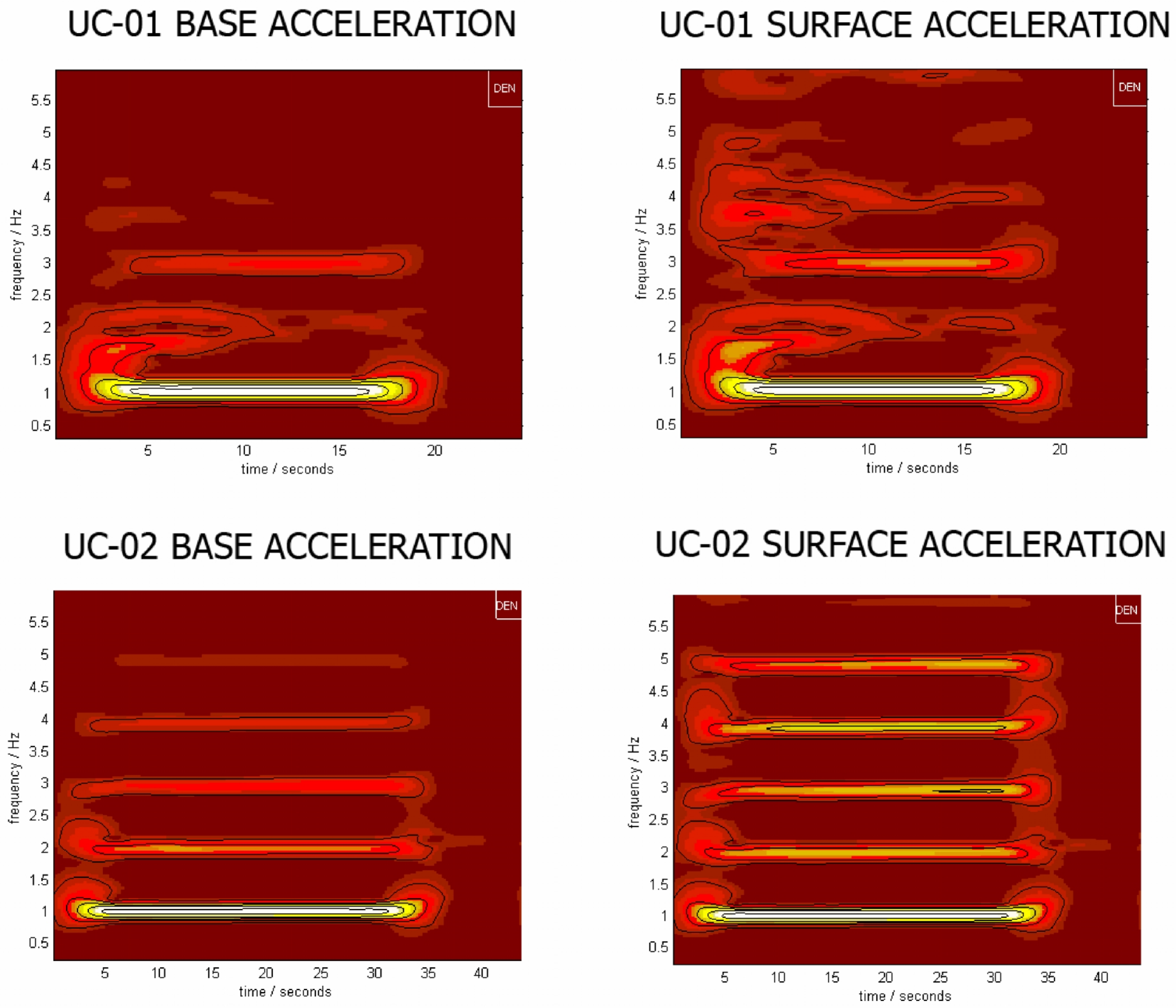

Fig.9. Wavelet plots for base and surface accelerations for UC-01 and UC-01 in prototype scale

4. DISCUSSION

Visual observations from the shaking table test revealed that the circular, flexible tunnels under low stress conditions show very strong soil-structure interaction. The tunnel model in shaking table experiment collapsed as a result of accumulated plastic strains in the tunnel lining, which is caused by strong ovaling motion. Large deformations and eventual collapse resulted in formation of failure surfaces. More information about the 1g-shaking table test on flexible tunnels are given by Cilingir and Madabhushi [15].

Visual observations from the centrifuge experiment on the flexible and shallow tunnel, on the other hand, shows that large confinement stresses keep the tunnel safe, although the embedment depth (2.5 m in prototype scale) and the stiffness of the tunnel lining are quite small.

Acceleration data from the centrifuge experiment suggests that amplification occurs both in free field and near the tunnel. This amplification effect can also be seen in the wavelet plots.

Wavelet plots also reveal that mostly the higher harmonic components of the earthquake motion are amplified. But it is not possible to make a comparison between control test and the test on the flexible tunnel, because the characteristics of the base accelerations are quite different for those two experiments as shown in figure 9.

5. CONCLUSION

It is seen that the confinement stresses play an important role in the resistance of the flexible, shallow tunnels against strong earthquake motions. A comparison between shaking table and the centrifuge tests shows that once the arching effect is mobilized, the tunnels resistance to large plastic deformations and the collapse increases, although the tunnel structure is very flexible compared to the surrounding soil. In shaking table tests, a strong soil structure interaction and large ovaling deformations has been observed. But it shall be known that exact similitude can not be achieved by shaking table tests [18]. Further analyses are required in order to capture the mode of deformation of the tunnel lining in centrifuge experiments.

Acceleration data and the wavelets analyses show that there is an amplification of the accelerations. Mostly the higher frequency components of the motion are amplified in both of the centrifuge tests. It may be due to presence of the tunnel structure in the soil. But, the frequency data for the control test is quite scattered, therefore further experimental work and analysis is required to make a better comparison.

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