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Experimental and numerical investigations of the effect of buried box culverts on earthquake excitation

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ABSTRACT

The seismic response of soils consisting of uniform sandy soils with two different relative densities *Dr* (50% and 90%) was investigated using the RPI geotechnical centrifuge facility, with a one-dimensional earthquake simulator at 60 g. The seismic soil structure interaction between the sand, buried box culvert, and surface foundations was also studied. The models were subjected to three earthquakes with different amplitudes and frequencies. Model settlements were recorded from 1 g to 60 g and during the seismic shakings; the ground response parameters were assessed. Rocking of structures was observed to be small for the box culverts compared to the surface foundation due to the soil confinement. The effect of kinematic soil structure interaction between the dry sand, box culverts and foundations was also explored. Kinematic soil culvert interaction was found to lead to a large reduction in the peak ground acceleration at the soil surface, which can reach up to 50%. Further numerical modeling was performed to investigate the effect of soil cover height on the kinematic soil culvert interaction and these results are also discussed in the paper.

1. Introduction

The effects of earthquakes appear in the form of seismic waves generated at bedrock level and can be transferred through a soil medium to the ground surface. These seismic waves can cause damage to existing structures either buried inside the soil or resting on the ground surface. In past earthquakes, it was believed that box culverts experienced little damage due to seismic waves, but in recent large earthquakes such as the 1995 Kobe, Japan earthquake, the 1999 Chi-Chi, Taiwan earthquake and the 1999 Kocaeli, Turkey earthquake, underground structures have experienced significant damage [1]. Youd and Beckman [2] inspected 11 box culverts in a zone within 10 km from the epicenter of the 1994 Northridge earthquake that were subjected to peak ground acceleration (PGA) ranging from 0.5 g to 1.0 g. There was no visible damage to any of these culverts, since they were well designed and constructed, and covered by compacted fill up to few meters thick. Nishioka and Unjoh [3] and Wood [4] stated that underground structures were thought to be relatively safe during earthquakes. However in the 1995 Kobe earthquake in Japan, six out of 21 subway tunnel stations suffered severe damage.

Chen et al. [5] performed a series of shaking table tests on scaled utility tunnel models with and without construction joints under non-uniform input earthquake excitation. The experiments were conducted in three phases. Phase 1 was a free-field test. Phases 2 and 3 were model tests in the longitudinal and transversal directions, respectively. The results demonstrate that the amplification factor at the same location decreases with an increase of PGA due to the development of soil nonlinearity. Displacement movements and rotations of the construction joint were mainly due to non-uniform excitation. For longitudinal vibration, the joint movements accumulated in one of the construction joints. For transversal vibration, the movements and rotations of different construction joints were similar. Structural response under non-uniform earthquake excitation was much higher than that under uniform earthquake excitation. It was

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Fig. 1. Models (a) strip foundation, (b) rectangular foundation, and (c) box culvert.

suggested that the effect of spatial distribution of earthquake excitation should be considered in the seismic design of utility tunnels.

Cilingir and Madabhushi [6] conducted centrifuge and numerical modeling to investigate the effect of different shallow depths of sand deposit on the seismic response of square tunnels with emphasis on the tunnel axis depth. The results showed that the depth of the tunnel does not affect the deformation pattern of the tunnel significantly during earthquake events. However the tunnel depth does affect the amount of amplification of acceleration through the tunnel, the magnitude of dynamic earth pressures and the magnitude of the lining forces. Amplification of the accelerations from bedrock to the top of the tunnel was also affected by the depth of the tunnel. Larger amplifications were observed for shallow models compared to deep models.

Cilingir and Madabhushi [7] used centrifuge and numerical modeling to investigate the effect of different input motion parameters, such as amplitude, frequency and duration on the seismic behavior of square tunnels. The results showed that the magnitude of the maximum input acceleration plays a crucial role in the maximum and residual lining forces, which the tunnel experiences. There was a strong dependence on input motion for the earthquake intensity and the bed rock accelerations.

Lanzano et al. [8] conducted a series of centrifuge tests on circular aluminum tunnels installed at different depths in sand with two densities. The results showed that the dynamic behavior of the whole soil mass was influenced by the position of the model tunnel at an offset of about twice the tunnel diameter from the tunnel center. Surface amplifications appeared to be still influenced by the cavity. Amplification at the surface of the sand layer was not significantly influenced either by the tunnel position or by the different initial density of the sand.

Besharat et al. [9] used finite difference modeling to investigate the variation in ground surface responses due to the presence of a circular tunnel. This study indicated that surface acceleration largely depends on the presence of the tunnel at a specific distance from the center of the tunnel. The greatest influence of the tunnel was at a distance of 0.5 D to 1.0 D from the center of the tunnel on the surface.

Tsinidis et al. [10] presented experimental work conducted in dynamic centrifuge tests on square tunnels embedded in dry sand. Horizontal acceleration was found to be amplified towards the surface. Also, the horizontal acceleration recorded for the roof slab of the tunnel was lower with respect to the acceleration at the same burial depth for the free field. Vertical acceleration-time histories recorded on the sides of the model roof slab were out of phase, indicating a rocking mode of vibration for the tunnel.

The current study examines the behavior of the sand, box culverts and foundations under seismic loading, by performing a series of dynamic centrifuge tests and numerical modeling using the FLAC software. A brief description of the centrifuge testing program and development of the numerical model and its

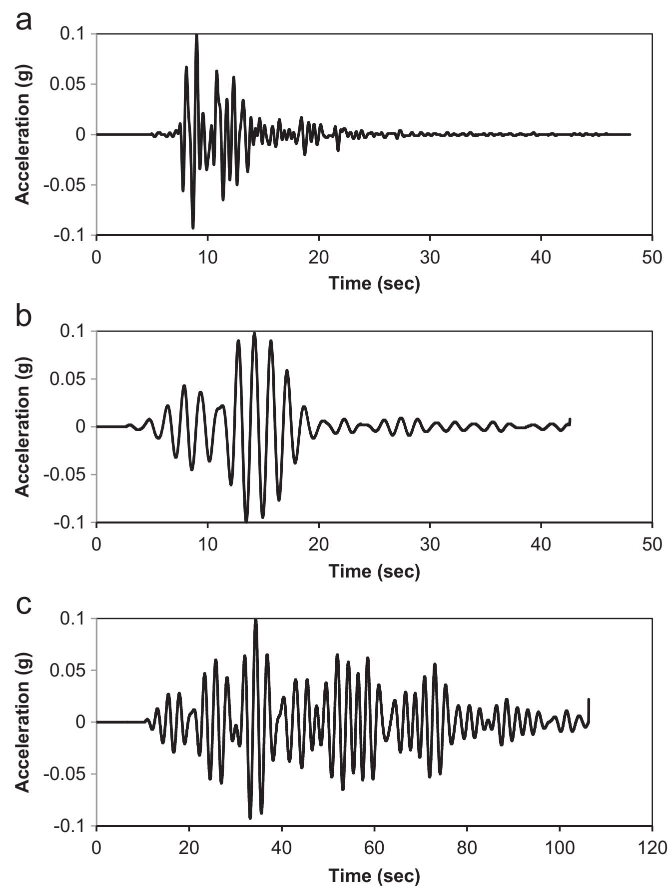

Fig. 2. Time histories for the: (a) Kobe, (b) Western Canada, and (c) Vancouver Cascadia earthquakes.

calibration/verification is introduced. In the centrifuge tests, the results were obtained from linear variable differential transducers (LVDTs) and accelerometers. In particular, the accelerometers were used to measure the acceleration time history at different locations. These locations were used to distinguish between the effect of the Free Field (FF), which is a well-known term for the zones where the soil movement is not influenced by the presence of a structure on the surface or buried inside, and the "Structural Field" (SF), where there is an effect from the structure. Data collected from the LVDTs and the accelerometers are presented. These show the settlement of the soil surface, the rocking of the foundations and box culverts, the lateral movement of the surface foundations, and the kinematic soil culvert interaction. The numerical model was calibrated and verified using the centrifuge test results. This information was then used to check the effect of the soil fill height to culvert width ratio (H/Bc) on the kinematic soil culvert interaction.