Centrifuge model tests of fault rupture effect on some geotechnical structures

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ABSTRACT

Three different problems are also described in the current paper i.e. the effect of faulting on buried pipes, segmental tunnels as well as shallow foundations. Effect of embedment depth as well as pipe type are investigated in the first study. In the second set of tests the performance of shallow foundations with different embedment depths and different contact pressures were studied. In the third study the behavior of segmental tunnels against faulting were the main subject. Interesting behavior of these tunnels are described and all failure mechanisms are introduced.

Keywords: centrifuge tests, surface faulting, buried pipes, shallow foundations, segmental tunnels

1 Introduction

Surface Faulting Rupture Hazard (SFRH) has been recognized as an important cause of damages to different structures during recent earthquakes. Extensive researches is going on for more than a decade on this subject. Fault rupture propagation through surface sedimentary layers is a major subject that is under study by means of numerical as well as experimental methods.

In the area of experimental studies particularly physical modeling, centrifuge model tests have had important role. In the current paper, two different fault simulator developed in University of Tehran are introduced. Since the "Surface Faulting Rupture Hazard" is an important issue particularly for urban buildings and infrastructures, this subject is of great importance for the country. Particularly, in densely populated Iranian cities such as Tehran and Tabriz, many buildings have been constructed adjacent or over fault outcrops.

Series of experiments were carried at the centrifuge facilities of the University of Tehran. This facilities consist of a beam centrifuge with a 3.5 m radius that can accelerate a model mass of 1500 kg at 100g.

Among the studies have been conducted, three types of researches are briefly introduced here. Effect of surface faulting rupture on shallow foundations and also on buried pipelines as well as on typical segmental urban tunnels of Iranian subway metro are introduced. Tests were conducted under centrifugal accelerations between 50g to 70g.

2 Centrifuge testing at University of Tehran

2.1 Centrifuge facility

Geotechnical centrifuge of engineering faculty of university of Tehran is the largest active geotechnical centrifuge set-up in Iran. The instrument is beam type centrifuge with a suspending basket. This facility is consisted of parts such as: a) suspending basket, b) centrifuge boom, c) adjustable counterweight, d) fluids rotary joint and electrical slip ring, e) driver system, f) aerodynamic covering, g) automatic balancing system and some minor parts which are indicated in Table 1.

Table 1. Centrifuge Facility Properties

| Property                        | Unit | Quantity |
|---------------------------------|------|----------|
| Exerted acceleration            | g    | 5 – 130  |
| Acceleration accuracy           | g    | + 0.2    |
| Rotational velocity range       | rpm  | 38 – 208 |
| Rotation radius                 | m    | 3        |
| Maximum model weight (up to 100 g) | kg | 1500     |
| Maximum model weight (up to 150 g) | kg | 500      |

Two faulting simulators are designed and manufactured. Both of them consist of a split box that are able to move in such a way that reverse as well as
normal faulting could be generated. Driving system in both simulators are remote control hydraulic units. One of the fault simulators is called FSUT-RN 60.8. This split box have been used in the cases that the shear rupture has to be directly applied to the buried structure. FSUT-RN 60.8 is made of aluminum alloy with dimensions of 102 * 76 * 68 cm (length * width * heights) and 2300 (N) weight. Dimensions of its split container are 96 * 70 * 23 cm. Dip angle of the fault in FSUT-RN 60.8 is 60 deg. (β =60°) and dividing the container into two unequal sections which the larger section forms the moving part and the smaller section forms the fixed part. The simulator is able to apply ± 4 cm offset in model scale and is designed for acceleration of 50 g. In other word the simulator is able to simulate ± 2 meters of faulting in the prototype scale.

Designed mechanism and some views of FSUT-RN 60.8 are shown in Figures 1 and 2. The rate of fault movement in this simulator is 20 cm/s in prototype scale.

Another fault simulator, known as variable dip angle fault simulator, has also been designed and fabricated with external dimensions of 1000 mm length, 500 mm width and 450 mm height and presented in Figure 3a. This apparatus has been built using steel, high resistance aluminum and transparent side walls.

The transparent side wall is made up of a 40 mm thickness Plexiglas plate which can observe the rupture propagation and capture its image during experiment. The split box, containing soil, has internal dimensions of 630 mm length, 490 mm width and 340 mm height (see Fig. 3b). This box is composed of stationary part (Footwall), movable part (Hanging wall), jack and cylindrical guide rod, Figs. 3c and 3d. Its movable part is actuated by an 18 ton hydraulic jack. By the way, the cylindrical guide rod helps the hanging wall in moving upward or downward with certain fault dip angle. The set of hydraulic jack is also bolted to the two fixities.

The split-box built in this study can be adjusted for four dip angles of 45°, 60°, 75° and 90°. The movable part of split box is connected to the fixed part by several frictional screws (Figures 3b and 3c). The dip angle of split-box can be adjusted by opening the screws, changing the angle of movable part and re-fixing them.

First series of tests have been conducted on buried pipes using FSUT-RN60.8 fault simulator. Many tests of reverse and normal faulting has been performed. Parameters such as type and dimensions of pipes, embedment depths, amount of fault dislocation and also mitigation methods for reducing the faulting caused failures on buried pipes have been studied.
Two different failure types of buried pipes are observed during reverse faulting of dip angle of 60° that are shown in Figure 4. Localized deformation was observed when the overburden soil had thickness of more than 3 times of the buried pipe diameter, whereas for the thinner overburden layer the beam buckling was observed.

Fig. 5. Wrinkling type of deformation of buried pipes

Another type of localized deformation is 'wrinkling type' as shown in Figure 5. Pipe section slenderness plays significant role in pipe deformation. Pipes with sections of D/t > 67 experience wrinkling or local buckling. Here t and D denote thickness and outer diameter of the buried pipe respectively. By increasing diameter and burial depth, deformation mechanism from beam buckling changes to local deformation and wrinkling one. These observations are well comparable to the observations of the performance of buried pipes during the real earthquakes.

4 Centrifuge model tests on surface foundations

Another series of tests that are briefly introduced here are those conducted on the effect of surface faulting on shallow foundations. The schematic view of the tested models is shown in Figure 6. The position of the foundation to the fault trace is assumed as 's' and the embedment depth is considered as 'D' while the width denoted by 'B'. Effect of the spacing of the foundations and embedment depth is studied by assuming different s/B and D/B dimensionless parameters. Considering different types of foundations (Type I to Type IV) different embedment and contact pressures are applied. Table 2 briefly summarizes the test properties. Figure 7 shows the displaced and rotated model foundations after application of faulting during tests MA-06, MA-07, MA-09 and MA-10. All foundation Type I to Type IV had a length of 485 mm and width of 170 mm in model scale. Embedment depth ratio D/B were 0, 0.3 and 0.6 for Type I to Type III respectively. D/B for foundation Type IV was 0.3. Contact pressure for Type I to Type III were 81 kPa whereas it was 40 kPa for Type IV in prototype scale.

The applied centrifugal acceleration was 50g. Application of the faulting has caused displacement as well as rotation of the model foundations. Considering the importance of rotation of the foundations that are assumed as rigid ones Figure 8 demonstrates the effect of faulting in different tests. As shown in both Figures 8(a) and 8(b), it is obvious that the embedded foundations has experienced larger rotation comparing to the surface located foundation regardless of their positions. However, as is shown in Figure 8(a) although the rotation of the model with D/B of 0.6 was larger than that of D/B of 0.3 at smaller dislocations, it has increased when dislocation was more than 0.57 m in prototype scale.

Table 2. Properties of model tests on shallow foundations.

| Test  | Foundation type | Embedment ratio D/B | Contact pressure, q (kPa) | Contact position, s/B |
|-------|-----------------|---------------------|--------------------------|-----------------------|
| MA-04 | -               | -                   | -                        | -                     |
| MA-05 | Type I          | 0                   | 81                       | 0.75                  |
| MA-06 | Type II         | 0.3                 | 81                       | 0.75                  |
| MA-07 | Type III        | 0.6                 | 81                       | 0.75                  |
| MA-08 | Type I          | 0                   | 81                       | 0.4                   |
| MA-09 | Type II         | 0.3                 | 81                       | 0.4                   |
| MA-10 | Type IV         | 0.3                 | 40                       | 0.4                   |

Fig. 6. Schematic view of the tests on shallow foundations

Fig. 7. Interaction of embedded foundation and reverse fault observed in (a) Test MA-06; (b) Test MA-07; (c) Test MA-09; (d) Test MA-10.

5 Centrifuge model tests on segmental tunnels

Another series of tests have been conducted on the segmental tunnels. The tunnels are assumed to be constructed inside soil layers and the rock tunnels are out of scope of this study. The segmental tunnels are commonly constructed using TBM facilities. Since some of subway tunnels are crossing major faults in the Iranian cities such as Tehran and Tabriz, the study has significance for this engineering projects. Figure 9 shows the schematic view of the test setup. Both reverse and normal faulting were applied to the model at different dip angles. Only a brief description on the
response of the tunnel to normal faulting is explained here. Normal faulting has caused the tunnel to bend in its longitudinal direction and therefore some damages could occur. Figure 10 shows the typical failure observed during the normal faulting.

Damages resulted from the tensional component of the normal faulting. The separation of the segments occurred in the critical rings located in the faulting zone. Separation at the crown of the tunnel caused the collapse of soil into the tunnel.

Figure 11 shows the progress of failure with increasing of the fault dislocation. Final and extreme failure was occurred in a fault dislocation of 1.4 m in prototype scale. It seems the weakness of the segmental tunnels when are subjected to normal faulting is their disability of tolerating the extension and separation of the segments.

Fig. 10. Typical failure of the segmental tunnel subjected to normal faulting

Fig. 11. Failures in segmental tunnels during normal faulting

6 Summary

Three types of centrifuge tests have been performed on the effect of surface faulting on buried pipes, shallow foundations and segmental tunnels. Tests were mostly conducted under 50 g centrifugal acceleration. Two split boxes are designed and fabricated. Both boxes were used during the tests.

A brief explanations on the behavior of buried pipes, shallow foundations and also segmental tunnels are explained.
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