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# DKSField investigation of liquefaction-induced damage due to the 2016 Meinong earthquake in the Shi-Din area of Taiwan

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**ABSTRACT:** The M 6.4 Meinong earthquake occurred at 3:57:27 a.m. local time on 6 February 2016 in Taiwan (19:57:27 on 5 February 2016 UTC). The earthquake, which took place just before New Year's Eve celebrations for the Lunar Year of the Monkey, killed at least 117 people. Liquefaction damage due to the earthquake occurred in the Shi-Din area in the Annan District of Tainan City. Damage observed in the area includes excessive soil boiling, lateral spreading of a sloped road, and tilting and settling of houses with shallow foundations. Soil profile in this zone is: the first 9m beneath the ground surface is consisted of loose sandy soils and silts with low SPT- N value, and followed by soft clayey soils and stiffer sandy layer to 20m depth. After the earthquake, houses built in continuous shallow foundation were found to experience maximum settlement 15 cm which is less than the ones built in individual shallow foundation experiencing the maximum settlement 120 cm and significant tilt. The main purpose of this paper is to document and analyze geotechnical problems encountered in this region affected by liquefaction.

**KEYWORDS:** soil liquefaction, 2016 Meinong earthquake, building damage, shallow foundation

## 1 INTRODUCTION

The magnitude 6.4 Meinong earthquake rattled Taiwan at 3:57:27 a.m. on 6 February 2016 (19:57:27 on 5 February 2016 UTC), one day before Chinese New Year's Eve. 116 people died in the structural collapse of a 16-floor building (Figure 1) in the worst-hit area of Tainan city. In particular, the coastal area of Shi-Din (meaning the top of the stream in Chinese) in Tainan consists mostly of soft soils that presented the most numerous geotechnical problems as a result of this earthquake. Observed effects in the area, where more than 300 houses locate in, include sand boils, settlement and tilting of buildings with shallow foundations, lateral spreading, and damage to diaphragm walls in buildings.

Such geotechnical damage caused by widespread liquefaction was also observed in the 1995 Kobe earthquake (Shibata et al. 1996), the 1999 Chi-Chi earthquake (Chu et al. 2004), the 2008 Wenchuan earthquake (Huang and Jiang 2010), the 2011 Christchurch earthquake (Bray et al. 2014), and the 2011 Tohoku earthquake (Ishihara 2012). The main purpose of this paper is to investigate the geotechnical damages in the Shi-Din area of the Annan district in Tainan due to the earthquake.

## 2 INVESTIGATION AND MAPPING OF LIQUEFACTION ZONES

The Annan district in Tainan is a reclaimed area of the old Taijian inner sea that has been used by humankind for more than a century. The Meinong earthquake excited the reclaimed soils in the Shi-Din area of the Annan district, causing them to significantly liquefy. The most severe and intensive soil liquefaction causing damages are found in this area. Area of the Shi-Din is around 0.2 Km<sup>2</sup> and with more than 300 houses locate in.

Most of the 2-to-4 story buildings in that area have shallow foundations and were built 30 to 40 years ago; these buildings experienced significant liquefaction-induced settlement. According to a borehole close by as shown in Figure 2, the upper 9 m of soil in the area consists of loose to medium density sand with a relative density of around 60% and a water table that is very close to the ground surface.

For flood prevention purposes, the low ground elevation of the Shi-Din area is protected by embankments with higher ground elevations. The ground elevations on both the north and south sides of the Shi-Din area have been found to be higher, with a difference of around 50 cm from the rest of the region.

The distribution of liquefaction features, as evidenced by sand boils on the ground, is shown on the map in Figure 2. Observe that the Shi-Din area, which is about 4 km away from the present coast and surrounded by two major drainage systems on the northern and southern sides denoting the extend of a former marginally marine area, is the region that experienced significant soil liquefaction. The light blue area on the map denotes zones of significant liquefied soils found after the earthquake. Sand boils that spread out on the road are 1- 3 cm thick in general and in drains can reach thicknesses as great as 25 cm. Highlighted features marked 1 to 4 are discussed. Houses A and B and Building C, which experienced some damage are investigated and discussed in the following sections.



Figure 1. The severest damaged spot in 2016 Meinong earthquake. 116 deaths are reported in this collapsed 16th floor building due to structure damage.

Satellite map of Taiwan



Figure 2 Location of the Shi-Din area and the hazard map (modified from Google map)

### 3. FIELD INVESTIGATION RESULTS AND DISCUSSIONS

After detailed field investigations conducted by the author, five localities were identified (marked on the map in Figure 2). These localities, which are introduced below, are numbered in sequence from south to north and east to west. Two drainage systems go through the regions on the north and south sides, which results in substantial local concern regarding the soundness of the embankments bounding this drainage and focusing attention on assessments of these features.

Locality No. 1: Lateral flow of liquefied soils on a sloping layer. A 15 cm elevation difference from south to the north at locality No. 1 is the result of lateral ground movement beneath liquefied soils (Figure 3). The horizontal movement is measured to be 12.5 cm with a vertical settlement of 3-5 cm at the top. The maximum heave at the middle of the road is measured to be 7 cm. Two abandoned houses have sat at this locality for around 30 years and both of their front slabs have an elevation difference of 55 cm with the original front road after the quake. It was alleged by the neighbors that the 25 cm out of the 55 cm took place because of the 2016 Meinong earthquake. The settlement before earthquake is indicative of consolidation of the soft clayey soil deposits beneath the foundations. Excessive liquefied deposits on the ground surface are found with a thickness of 25 cm in this locality. Sixteen houses at top of the sloped ground are kept from being dragged down slope by their continuous shallow foundations.

Locality No. 2: Greatest settlement of shallow foundations in the Shi-Din area.

Two individual houses, each with three floors were studied at this location. A larger house with a length of 10.0 m and a width of 10.0 m settled into the ground to a maximum depth of 120 cm and a second smaller house with relatively smaller area with a length of 9.0 m and a width of 8.0 m exhibited 30 cm of settlement. The two houses have separate foundations that are aligned with each other in a west-east direction, separated by a distance of only 3 m. Therefore, the settlement of the houses pushed soils to the roadway running between the houses, an

area relatively free of overburden, and thereby heaving up the road. In addition, because the space between the two settled foundations is narrower than the widths of the buildings, both of the houses tilted toward the central roadway. The first house, with its heavier mass, tilted more than the second house, and both of the W-E facing features fit the direction of the earthquake recorded at station Tainan, the closest station, with a peak ground acceleration of 0.23g to the west. Other than tilting to the west, the first house also steeply tilted to the south because of an open space on its south side. The second house, however, showed much less north-south directional tilt because of the brick structure on its south side. Figure 4(a)(b) shows the settlement and tilt of the houses.

Locality No. 3: 20 cm settlement of the individual shallow foundations of a three-story building

This building, used as a car repair center, is taller and heavier than its neighbors with an individual shallow foundation as shown in Figure 5. After the earthquake, the house was found to tilt to the west. The settlement of its shallow foundations amounted to 20 cm, and a pipeline in front of the house was bent at an angle of 30°. The houses closest to this building are all two-story houses with continuous foundations. These houses experienced limited settlement and very little interior cracking. Such minimal damage suggests that when liquefaction-induced soil instability is minimized, foundations – and the buildings constructed on them – can avoid structural damage in this region. Also, such observations reveal that in addition to the serious consideration of earthquake hazards in the structural design of buildings, we should also consider the geotechnical design, especially related to soft and liquefiable soils.

Locality No. 4: 10 to 15 cm settlement of shallow house foundations

Ejected soil deposits spread around on the ground surface with a thickness of 3 cm. Many liquefied soils could be found between the walls of houses and on the ground. Inside some extended structures, liquefied soils were spread on the ground surface. Soils were mostly extruded from the interfaces between new and old structures where cracks and fissures exist. Note that pipeline construction had just been carried out at locality No. 4 by a pipe jacking method within the two months leading up to the earthquake. On a two-way road at locality No. 4, the lane that the pipeline travels beneath was found to have a greater amount of sand boiling on the ground surface and also relatively larger settlement.

Locality No. 5: 7 to 15 cm settlement of shallow house foundations.

The row houses at locality No. 5 settled considerably less than those at locality No. 4. Due to uniform settlement, the structure of houses did not suffer too much obvious damage, but major problem occurs on structural extensions. Most of the houses at this locality extend the use of their back gardens into indoor areas enclosed by walls and covered by roofs. The extended areas showed obvious differential settlement relative to the main structures. Cracks were found in both walls and floors. In addition, soil footprint could be found in toilets, bathrooms, drainage pipes and cracks in structural interfaces.

Figure 6 shows the general phenomenon of continuous shallow house foundations at locality Nos. 4 and 5. Most of the 30- to 40-year-old main house structures remain in a sound condition, but extensions, which sometimes were only 10-20 years old, were often deformed due to differential settlement.

#### 3.1 Embankments along the drainage systems in the north and south

The author and his teammates investigated the embankments, which in relative terms are 50 cm higher in elevation than the locations of significant liquefaction occurrences associated with the two drainage systems. They checked not only the soundness of the embankment structure but also the soil conditions of the

adjacent flood plains. This fieldwork showed that there has been no obvious earthquake-induced damage to the embankment- or deformation of the soils on flood plains- in this dry season.

### 3.2 Diaphragm wall damage

The tallest buildings in the Shi-Din area are several 13-story buildings with 1 basement level, which were constructed by the same contractor 18 years ago (see Building C in Figure 2). The location of the buildings is close to the northern drainage system, which has a relatively higher elevation and where no liquefaction occurrence has been observed. The earthquake induced damage was found at diaphragm wall and 3 different columns. The damaged spot of the wall and columns is all around 1.5 m beneath the ground surface and it was accompanied by groundwater leakage. It also can be seen (Figure 7) that the steels inside the damaged spot have already rusted heavily, thereby revealing that a detailed examination of the strength of the walls and columns should be carried out.



Figure 3(a). Lateral spread at Locality 1. The heave at the middle of the road is as much as 5-7 cm.



Figure 3(b). Lateral spread at Locality 1. The 12.5cm gap at the top of the slopped road.

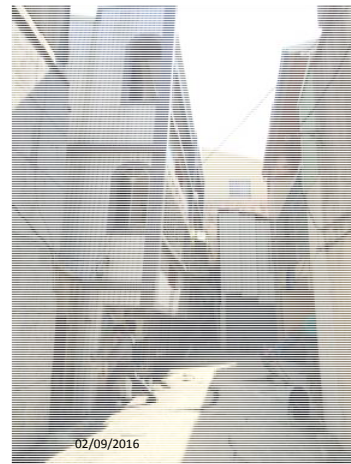


Figure 4(a). Two shallow founded houses at Locality 2 settled in Shi-Din area. The white house on the left side of the picture settled maximum 120 cm and the yellow house on the right side settled 30 cm. The middle of the road was heaved up.

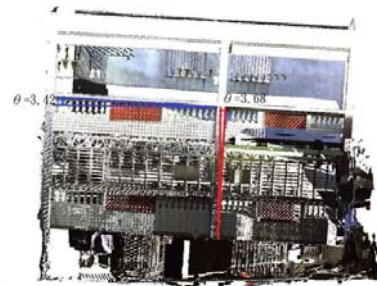


Figure 4(b). The front view shown by object-based point cloud analysis



Figure 5(a) and (b) The car repair center faces to the west side with an individual shallow foundation at Locality 3 settled 20 cm and slightly tilted to the west.

## 4. LIQUEFACTION POTENTIAL OF THE AREA

Of the different types of in-situ tests available, and because of the extensive databases and record of past experiences, a standard penetration test (SPT) is generally the preferred option for assessing the liquefaction potential of sediments in a given area. Seed and Idriss (1971) proposed a basic simplified method. This procedure has since been modified and improved by several researchers (e.g., Seed et al. 1985; Youd et al. 2001). The modified method has been used in this paper to evaluate liquefaction potential in the Shi-Din area. After the factor of safety is determined for each depth, as  $SF \leq 1$ , liquefaction is said to either occur or not occur.

According to soil exploration in the area, a 20-m-thick soil profile is simplified as four layers consisting of a sand-mud mixed layer, a sandy layer and another harder sandy layer and, finally, a clayey layer. In this profile, the first 4 m beneath the ground surface consists of sandy soils with 20%-40% fine content and an SPT N-value from 4-8. After that, it follows sandy layer with SPT N-value around 10 and then harder sandy soils with a 20 SPT N-value for 4 m. The last layer consisted of clayey soils with a 6 SPT N-value.

PGA is determined to be 0.16 g, according to the station from NCREE. The CSR is, therefore, obtained as 0.3. The values of CSR that pertain to the equivalent uniform shear stress induced by an earthquake of a given magnitude, were adjusted to an equivalent CSR for an earthquake of magnitude 7.5 through the introduction of the magnitude scaling factor (MSF) which accounts for the duration effect of ground motions. MSF is obtained as 0.6 as the recorded magnitude is 5 in the region. On the other hand,  $(N1)_{60cs}$  is obtained as 6.11. A safety factor for the 9 m sandy soil layer is estimated as 0.6, which is smaller than 1 and can be judged to liquefied soils in this earthquake. Excessive ejected soils were observed after the earthquake on the ground surface in this area, which fits this judgment.



Figure 6. The settlement on the road and shallow founded houses settled on at Locality 4 and 5. Some damages were found on the extended structure and mostly the main structure remains fine



Figure 7 the damages of the walls and columns of basement of a relative tall building (Building C) in Shi- Din area. The rusted steels were found inside the cracks of the wall.

## 5 CONCLUSION

Four types of liquefaction related phenomena have been observed in the Shi-Din area as a result of the 2016 Meinong earthquake. These are sand boiling, settlement of shallow foundations, tilting of shallow foundations, and lateral spreading. In addition, damage to diaphragm walls and columns

has been found in the basements of relatively tall buildings in this area.

The Shi-Din area has been evaluated as a zone of high liquefaction potential using a simple evaluation method. Soil liquefaction occurrence in the 2016 Meinong earthquake was observed excessively in this area and is demonstrated on the map of this area.

The 30- to 40-year-old two-story row houses in the area mostly have continuous foundations that successfully prevented them from experiencing larger liquefaction-induced settlement. On the other hand, newer three-story houses in the zone of liquefaction occurrence, with individual shallow foundations, experienced 25 to 120 cm of settlement accompanied by a significant tilt after the earthquake. This difference shows that building materials and construction methods should be considered, along with attention to geotechnical issues. Two individual founded 4- story houses experienced a tilt to north and south because of the lateral displacement of ground.

This area is the only place in Tainan to have experienced significant damage from soil liquefaction as a result of the Meinong earthquake, and fortunately the liquefaction hazard resulted in relatively limited damage to residences and buildings. No deaths have been recorded because of liquefaction.

The embankment areas along the rivers did not experience significant soil liquefaction because of the dry season and higher ground elevations. However, liquefaction-induced lateral spreading was found within 20 m of the embankments. A detailed investigation of the soundness of embankment is recommended.

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