Test Investigation on Liquefied Deformation Structure in Saturated Lime-Mud Composites Triggered by Strong Earthquakes

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Abstract: Three identical model boxes were made from transparent plexiglass and angle iron. Using the method of sinking water and according to the sedimentary rhythm of saturated calcium carbonate (lime-mud) intercalated with cohesive soil, calcites with particle sizes diameters of ≤ 5 μm, 10–15 μm and 23–30 μm as well as cohesive soil were sunk alternatively in water of three boxes to build three test models, each of which has a specific size of calcite. Pore water pressure gauges were buried in lime-mud layers at different depths in each model, and connected with a computer system to collect pore water pressures. By means of soil tests, physical property parameters and plasticity indices (Ip) were obtained for various grain-sized saturated lime-muds. The lime-muds with Ip ranging from 6.3 to 8.5 (lower than 10) are similar to liquid saturated silt in the physical nature, indicating that saturated silt can be liquefied once induced by a strong earthquake. One model cart was pushed quickly along the length direction of the model so that its rigid wheels collided violently with the stone stair, thus generating an artificial earthquake with seismic wave magnitude greater than VI degree. When unidirectional cyclic seismic load of horizontal compression-tension-shear was imposed on the soil layers in the model, enough great pore water pressure has been accumulated within pores of lime-mud, resulting in liquefaction of lime-mud layers. Meanwhile, micro-fractures formed in each soil layer provided channels for liquefaction dewatering, resulting in formation of macroscopic liquefaction deformation, such as liquefied lime-mud volcanoes, liquefied diapir structures, vein-like liquefied structures and liquefied curls, etc. Splendid liquefied lime-mud eruption lasted for two to three hours, which is similar to the sand volcano eruption induced by strong earthquake. However, under the same artificial seismic conditions, development of macroscopic liquefied structures in three experimental models varied in shape, depth and quantity, indicating that excess pore water pressure ratios at initial liquefaction stage and complete liquefaction varied with depth. With size increasing of calcite particle in lime-mud, liquefied depth and deformation extent increase accordingly. The simulation test verifies for the first time that strong earthquakes may cause violent liquefaction of saturated lime-mud composed of micron-size calcite particles, uncovering the puzzled issue whether seafloor lime-mud can be liquefied under strong earthquake. This study not only provides the latest simulation data for explaining the earthquake-induced liquefied deformations of saturated lime-mud and seismic sedimentary events, but also is of great significance for analysis of foundation stability in marine engineering built on the soft calcium carbonate layers in neritic environment.

Key words: simulation test, saturated lime-mud, liquefaction-induced deformation, lime-mud volcano, earthquake

1 Introduction

A strong earthquake causes liquefaction of water-saturated sand and silt soils in the seismic zone, and produces macroscopic veins of liquefied sand and 'sand volcanoes' (Plaziat et al., 1990; Purser et al., 1993; Du et al., 2005, 2007, 2008; Owen and Moretti, 2011; Li et al., 2013; He et al., 2015; He and Qiao, 2015; Tian et al., 2016), as commonly detailed in textbooks (Pan and Li, 2004; Chen, 2005; Shi, 2007), and confirmed by experiments and tests (Liu and Xie, 1984; Feng, 1989;
Owen, 1996; Jing et al., 2004; Li et al., 2005). It is less clear, however, whether water-saturated and soft calcium-carbonate sediments also become liquefied by strong earthquakes? Because these sediments are, as a rule, preserved below a marine sedimentary surface, so that it is impossible to witness seismic effects, hardly deals with this question no earthquake simulation test such presented here has been reported for water-saturated soft sediments. However, many references described that soft calcium-carbonate sediment could undergo liquefaction and form microsparite veins quite like the veins of liquefied sand affected by seismic activity (Qiao et al.,1994, 2002, 2007; Qiao and Gao, 2000; Du et al., 2001; Tian et al., 2003, 2006; Zhang et al., 2007; Tian et al., 2013, 2015a; Yang et al., 2015); records of seismically-induced liquefied lime-mud volcanoes also existed (Chi et al., 1999; Tian et al., 2013; Su et al., 2014). These earthquake records were identified mainly using the uniformitarianism principle ('the present is the key to the past'), petrologic methods and morphological comparisons. Since there is no experimental verification, natural liquefaction of soft water-saturated calcium-carbonate layers remains a controversial topic in the academic circles. Especially about the genesis of microsparite veins (the grain diameter of micritic calcite is mostly 5–15 μm, with a maximum up to 30 μm) in the Mesoproterozoic and Neoproterozoic, the debate about a seismic or non-seismic origin is going on already for a long time. It is commonly postulated that the veins were formed in soft water-saturated carbonate sediment by earthquake-induced liquefaction(Qiao et al.,1994, 2002, 2007; Failchild and Song,1997; Pratt,1998; Qiao and Gao, 2000; Du et al., 2001; Zhang et al., 2007), but this has also be contradicted (Furniss et al., 1998; Jams et al., 1998; Ge et al., 2003, 2004; Meng et al., 2006; Kuang et al.,2009, 2011). Meng et al. (2006) stated that microspar grains with a 5-15 μm diameter are not susceptible to liquefaction (i.e. consistent with the range of unconsolidated clay indicated by Lowe in 1975), according to the Lowe's graphic (Lowe, 1975); sediments built of micritic calcite particles of this size range should therefore not become liquefied, and their deformation would not be related to an earthquake. This raises some questions. Are the physical properties of micro-spar calcite and clay the same? Are state indexes of soft water-saturated clay and lime-mud alike? Because water-saturated clay has a strong cohesion, liquefaction does not take place by an earthquake, which is the consensus in the scientific community (Pan and Li, 2004; Chen, 2005; Shi, 2007). Will a strong earthquake cause liquefaction of water-saturated sediments built by calcite particles? And if so, how exactly will they be deformed? In order to answer these questions, soil tests were carried out and earthquake-simulation tests were performed.

2 Materials and Methods

Grey to light grey micritic limestone rubble with 96%–98% calcite was mined as raw material and processed into calcite particles with diameters of ≤ 5 μm, 10 μm, 15 μm, 23 μm and 30 μm. The calcite particles then were bagged, marked according to their particle diameter. Random sampling testing indicates that all calcite particles met the requirements regarding their grain diameter. It is worth noting that the high-purity limestone particles were greyish-white to white. Red-brown cohesive soil was sampled, crushed and screened, thus getting the appropriate properties for cohesive soil material that could be used for the experiments in the boxes. The cohesive soil was composed mainly of kaolinite and illite, containing silt 4.0%–5.6% of silt and about 1.5% of organic matter.

The earthquake-simulation model and the distribution of the sedimentary soil layers are shown in Figure 1a. Transparent plexiglass of 8-mm thick and a steel frame of 5 mm thick were used for the construction of three identical boxes with dimensions of 67 cm × 50 cm × 100 cm (L × W × H). A 3.5% NaCl salt solution (pH=8.5 or so) was poured into the boxes to simulate seawater. The calcite particles and the cohesive–soil material were slowly put into place in the water-filled boxes, forming soft water-saturated carbonate layers of 12–13 cm thick each, and cohesive soil layers of 4–7 cm thick each; this procedure took 56 days.

The grain diameters of the calcite particles in the three boxes were respectively ≤ 5 μm (0.005 mm), 10–15 μm (0.010–0.015 mm) and 23–30 μm (0.023–0.030 mm). A pore-water pressure gauge (type: GSY-2; range: 0.05 MPa) was buried in a white carbonate layer and connected with a system that collected real-time data for the pore-water pressure (Fig. 1b) that was composed of pore-water pressure gauges, a pore-water pressure data collector (type: GPC-8), a converter, and a PC equipped with a control program. All instruments and the software were manufactured by Dandong Sanda Instrument Co., Ltd. After test-models had been constructed, the middle part of each soil layer sank slightly under the action of its own weight for 74 days. Because of the boundary osmotic effect, the contact planes between the bottom of the carbonate layers and the top of the successive cohesive soil layer were irregular. It can, however, not be fully excluded that some sedimentary deformation structures developed because of unstable vertical density gradients before the earthquake-simulation test was started.
According to the latest published edition of 'Sedimentology in China' (Feng, 2013), sediment clasts with grain diameters of $\leq 5 \mu m$ and 10–30 $\mu m$, respectively, are mud and silt; for carbonate sediments with particle sizes of $\leq 5$–30 $\mu m$, it is, however, more appropriate to use the commonly used term 'lime-mud'. The grain diameter of lime-mud was defined as $<0.03$ mm (30 $\mu m$) by Liu (1980), and therefore the term 'lime-mud' is adopted here to describe the above water-saturated carbonate sediments with different grain diameters.

Based on the conventional method for soil tests, several sedimentary soil samples were taken from the test boxes to determine the main physical properties and state indexes of the water-saturated lime-mud. For the earthquake-simulation tests, an artificial seismic source was generated at the bottom of the model by means of artificially inducing seismic waves. The methods and processes were more specifically the following: an flat iron cart with rigid wheels (with diameters of 15 cm) was pushed at a speed of 2–3 m/s; the wheels continually touched a stone step of 5 cm high three times within six seconds, and thus formed a point-like artificial seismic source (Fig. 1b). According to the kinetic energy formula and the test of Chen et al. (2007), the kinetic energy from the epicentre was 7,500 J, equivalent to an orthodox explosive of 3.75 g. This new method of earthquake testing and research, with artificially induced seismic waves, is economical, flexible and environment-friendly (Chen et al., 2007; Fu et al., 2010). Already several years ago, this earthquake-simulation test method was applied to sandy soil liquefaction tests to investigate the formation of seismites origin, and validation yielded good results (Yan et al., 2007, 2009).

### 3 Test Results

#### 3.1 Soil test

The soil test results are shown in Table 1. It appears that, along with an increasing diameter of the calcite particles, the density of the water-saturated lime-mud becomes larger; in contrast, the water content, the void ratio and the plasticity index become smaller. Because the cohesive soil is defined as a soil with plastic index larger than 10, the soil under study belongs to the non-liquefied soil (Chen, 2005; Shi, 2007). As the plasticity indexes of

<table>
<thead>
<tr>
<th>Model number</th>
<th>Name</th>
<th>Particle diameter ($\mu m$)</th>
<th>Gravity density $\gamma$ (kN/m$^3$)</th>
<th>Water content $w$ (wt%)</th>
<th>Porosity ratio $e$</th>
<th>Saturation degree $S$ (%)</th>
<th>Plasticity index $Ip$</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Calcite particle</td>
<td>$\leq 5$</td>
<td>19.0</td>
<td>29.3</td>
<td>0.769</td>
<td>99.0</td>
<td>8.5</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Calcite particle</td>
<td>10–15</td>
<td>19.3</td>
<td>25.8</td>
<td>0.662</td>
<td>99.0</td>
<td>7.6</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Calcite particle</td>
<td>23–30</td>
<td>19.4</td>
<td>20.7</td>
<td>0.449</td>
<td>100.0</td>
<td>6.3</td>
<td>4</td>
</tr>
<tr>
<td>1–3</td>
<td>Silty clay</td>
<td>$\leq 10$</td>
<td>18.9</td>
<td>29.0</td>
<td>0.764</td>
<td>97.0</td>
<td>14.7</td>
<td>4</td>
</tr>
</tbody>
</table>

Notes: Gravity density ($\gamma$), gravity of soil in the unit volume; Water content ($w$), the percentage of water mass to soil particles’ mass in soil; Porosity ratio ($e$), a ratio of the pores’ volume to the soil particles’ volume in soil; Saturation degree ($S$), the degree for filling water in soil pores; Plasticity index ($Ip$), the difference of the liquid-limit and the plastic-limit of soil, but omitting %.

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Fig. 1. Earthquake simulation test model (a) and test instruments and methods (b).
all three types of lime-mud are less than 10 (Ip<10), and as the physical properties of the lime-muds are similar to those of liquefiable water-saturated siliciclastic silt, it must be deduced that the lime-mud may become liquefied under earthquake conditions (Chen, 2005; Shi, 2007). According to the physical meaning of the plasticity index, a soil with the plasticity index of over zero (Ip > 0) possess a certain cohesion. Obviously, all types of lime-mud used in the experiments described here are some cohesive, however, the lime-muds are less than the cohesive soil or silt with the same plasticity index, as will be discussed below. Due to the plasticity indexes of the three types of water-saturated lime-mud with different calcite particle diameters (Table 1), the degrees of liquefaction and the effects of an earthquake will be different for tests with the same earthquake–intensity conditions. The average plasticity index of the cohesive soil used for the three test models is 14.7 (Table 1, Ip) in the present study. Since its plasticity index is over 10 and under 17 (10<Ip<17), the soil is classified as silty clay (Chen, 2005).

3.2 Earthquake simulation test

When the wheels of the model cart violently hit the stone step at high speed to generate an artificial earthquake, the soft-sediment layers in each model box underwent significant changes, and the upper water-saturated lime-mud layer in all the models produced upward directed flows of liquefied material, forming phenomena that were similar to sand volcanoes triggered by strong earthquakes, including outbursts of a 'lime-mud volcano', formation of veins of liquefied lime-mud, liquefied diapir structures, micro-fractures and other deformation structures (Figs. 2–4). The depths of the soil layers that became liquefied differed in the various tests, and the intensity and the duration of the macroscopic

![Fig. 2. Liquefaction-induced lime-mud volcano and other deformation structures of the soft lime-mud layer (Calcite grain diameter ≤ 5 μm) in Model 1.](image-url)
outflow of liquefied lime-mud were also different. The real-time data collecting system for the pore-water pressure also monitored different data.

3.2.1 Macroscopic liquefaction-induced deformations in three test models

The macroscopic liquefaction-induced soft-sediment deformation structures consist of lime-mud volcanoes, veins of liquefied lime-mud, flame structures, etc. Apparently, they are also macroscopic signs that indicate the occurrence of liquefaction.

(1) Liquefaction-induced deformations in Model 1

In this model (particle sizes of lime-mud layers were ≤ 5 μm), macroscopically visible liquefaction occurred in the uppermost 20–30 cm. Only a few lime-mud volcanoes developed. However, from the beginning of the outflow of liquefied material (Fig. 2a) to the expansion of the lime-mud volcanoes (Fig. 2b–c), lime-mud volcanoes, vein-like structure of liquefied lime-mud, diapir structures of liquefied lime-mud, micro-faults and other deformation Structures increased in size and in number. The outflow of liquefied lime-mud lasted for about two hours. In the plane view, the lime-mud volcanoes are very similar to sand volcanoes formed by present-day earthquakes (Fig. 2d). The simulated earthquake induced a slightly undulating top of the sedimentary layers.

(2) Liquefaction-induced deformations in Model 2

In Model 2 (particle sizes of lime-mud layers were 10–15 μm), the maximum depth of liquefaction-induced deformation was 50 cm. The outflow of the lime-mud forming volcanoes lasted for about 2.5 hours. Compared with the first model, the liquefaction now reached a larger depth, more lime-mud volcanoes developed and the outflow of liquefied lime-mud lasted longer. These features indicate that the liquefaction was more intense (Fig. 3). From the beginning of the outflow of liquefied lime-mud (Fig. 3a) to the phase of strong outflow of lime-mud (Fig. 3b), the volcanic conduit became wider, and developed downwards along micro-faults, which was accompanied by more violent liquefaction and outflow. Fig. 3c shows that the outflow of the liquefied lime-mud broke up the overlying cohesive soil layer, forming even greater diapirs and intrusive bodies of liquefied lime-mud (Figs. 3c-④ and Fig. 3c-⑥) and a liquefied lime-mud mass (Fig. 3c-⑦) in addition to the various liquefaction-induced deformations mentioned above. The lime-mud volcano shown in Fig. 3-e remained buried under the overlying cohesive soil, which shows that the lime-mud outflow was supported by a strong invasive force that came from the excess pore-water pressure. In plan view the lime-mud volcanoes are quite similar to those formed by present-day earthquakes (Fig. 3d); its volcanic edifices (craters, cones, main conduit, sub-conduit and muddy xenoliths) are also distinct (Fig. 3e).

(3) Liquefaction-induced deformations in Model 3

In this model, diameters of the calcium-carbonate particles were 23–30 μm, which is same as the diameter of silty sand. The water-saturated sedimentary layers were highly sensitive to earthquake-induced liquefaction, and the maximum liquefied depth was 75 cm. Earthquakes-triggered liquefaction was more violent than in the other experiments, and formed fairly dense lime-mud volcanoes (Fig. 4a and e). The outflow of liquefied lime-mud led to a 2 cm high spewing column (Fig. 4b). As shown in Fig. 4c, veinlike structures of liquefied lime-mud formed by diapirism are very similar to molar tooth structures. In addition to the seismic deformation structures that also developed in experiments 1 and 2, liquefaction-induced curled fold structures were also found at some places (Fig. 4d). The outflow of the lime-mud volcanoes lasted for about three hours. Distinct undulating deformations took place at the top of the soil layers (Fig. 4a–b).

3.2.2 Excess pore-water pressure ratio and its changes

The excess pore-water pressure ratio (γ_u) is an important parameter that was measured in the earthquake-simulation tests to determine whether it could generate liquefaction of the water-saturated sediments (Chen, 2007; Fu et al., 2010). In water-saturated sediments, the pores are fully filled with water. The pressure of the water in pores in a steady state is called the 'pore-water pressure'. When the sediment undergoes seismic vibration (shear stress), the pressure rises, and the increased part of the pore-water pressure is called the 'excess pore-water pressure'. The ratio between the excess pore-water pressure and the effective stress around the pores is called the 'excess pore-water pressure ratio' (γ_u). The effective stress around the pores of a water-saturated sediment at a certain depth is the sum of the effective gravity stress of the overlying sediment, the effective intergranular frictional resistance and cohesion (Chen, 2005; Shi, 2007). Water-saturated non-cohesive sediments (such as sand and silt) that are affected by earthquakes have excess pore-water pressure ratios of γ_u = 1, which implies that the sediment becomes entirely liquefied (Chen, 2007; Fu et al., 2010). The earthquake-simulation tests made by Sun et al.(2009) and Fu et al.(2010) in the engineering scene showed that water-saturated sand begins to liquefy when γ_u = 0.5–0.6. Because the pores of cohesive soil are quite small, and because the soil-particle surface is charged negatively, thus attracting polar water molecules, and because the intergranular cohesion is strong when water-saturated cohesive soil is affected by an external force, only a slight pore-water pressure is generated in the pores, which is too
Fig. 3 Lime-mud volcano and other deformation structures of the soft lime-mud layer (calcite grain diameter: 10–15 μm) in Model 2.
(a), Lime-mud volcano, flame structure and seismically-induced micro-fractures formed during the initial phase of the artificial earthquake; (b), Volcanic conduit extended deeply along micro-faults to the lower liquefied layer, and intensely outflown liquefied lime-mud, resulting in the formation of lime-mud volcanoes; (c), Outflow of liquefied lime-mud broke the overlying cohesive soil layers; (d), plan view of a lime-mud volcano; (e), cross-section through a lime-mud volcano before the new cohesive soil layer shown in Photo c was put in place. ① lime-mud volcano; ② volcanic conduit; ③ veinlike structure of liquefied lime-mud; ④ diapir structure of liquefied lime-mud; ⑤ micro-fracture filled with thixotropic mud; ⑥ intrusive body of liquefied lime-mud; ⑦ isolated liquefied mass.
small to overcome the effective stress around the pores, thus failing to induce liquefaction. However, once under seismic oscillatory shear stress, water-saturated cohesive soil may become thixotropic (i.e. it becomes less viscous and shows a stronger rheological performance) (Chen, 2005; Tian et al., 2015b). Figures 2–4 show that saturated cohesive soil, when affected by an earthquake, can generate small micro-fractures, providing conduits that allow the escape of water/sediment mixtures, which results in veins of liquefied lime-mud and in lime-mud volcanoes. Based on the combination of liquefaction phenomena and the excess pore-pressure ratio $\gamma_u$, we can accurately determine the liquefaction of water-saturated sediment and the degree of liquefaction at a certain burial depth. Fig. 5 shows the excess pore-water pressure ratio vs. time curves ($\gamma_u > 0.5$) in the tests within 200 s after the simulated earthquake. According to Figure 5, the lime-mud layers with an excess pore-pressure ratio $\gamma_u$ equal to or close to 1 are: the layer with Gauge P1 in Model 1, and the layers with Gauges P1 to P3 in Models 2 and 3. Obviously, these
lime-mud layers were completely or almost completely liquefied by the artificial earthquake. Because of $\gamma_u = 0.78-0.92$, which is $> 0.6$, as recorded by Gauge P4 in Model 3, the lime-mud layer at a depth of 57 cm in Model 3 was liquefied relatively strongly. The $\gamma_u > 0.5$ recorded by Gauge P2 in Model 1, Gauge P4 in Model 2 and Gauge P5 in Model 3, which the reflected lower liquefaction degree of the lime-mud layers in the three models, is basically consistent with the macro-liquefaction records shown in Figs. 2–4.

In summary, with increasing grain diameter of the calcite particles in the lime-mud, the plasticity index of the water-saturated lime-mud diminishes (Fig. 6a), whereas the liquefaction depth and the liquefaction intensity of the water-saturated lime-mud increase (Fig. 6b and Figs. 2–4).

### 4 Discussion

#### 4.1 Analysis of the forces and deformations for the model and the soil layer

When the wheels of the model cart moved horizontally, they collided with the stone step to generate an artificial earthquake (Fig. 1b); the model box and the soil layers in it underwent unidirectional horizontal squeezing and shearing, then a rebound generating horizontal tension and shearing, which formed cyclic loads of squeeze–tension with shear forces (Chen, 2007; Sun et al., 2009). Under the cyclic loads, the water-saturated lime-mud generated an excess pore-water pressure that was high enough to trigger liquefaction. At the same time, the generation of co-seismic micro-fractures provided dewatering channels, which allowed liquefied lime-mud to Intruded upwards along the micro-fractures to form veins, flame structures and lime-mud volcanoes. Part of the cohesive soil was swallowed by the large intrusive body of Liquefied material, which formed muddy xenoliths (Figs. 3e and 4b-⑥). Part of the liquefied structures was torn by the shear force to form liquefied masses (Figs. 4b-⑥ and 4c). Some veins of liquefied lime-mud and thixotropic mud were

**Fig. 5. Excess pore-water pressure ratio-time curves in test models ($\gamma_u > 0.5$).**

**Fig. 6.** Relationships between the grain diameter and the plasticity Index (a), and between the grain diameter and the liquefaction depth (b).
strongly squeezed, and formed curl-shaped deformations.

4.2 Earthquake intensity and boundary conditions

Liquefaction of water-saturated sand can take place only if the earthquake intensity has a magnitude of $M_s = 5$, and if the seismic intensity is of at least degree VI (Pan and Li, 2004; Chen, 2005; Shi, 2007). The calcite particles applied in the tests described here were much smaller than the sand size fraction, so that liquefaction needed a shock of over degree VI. It must consequently be deduced that the seismic intensity of simulated earthquakes in the experiments had an intensity of over degree VI. Considering the many co-seismic micro-faults and the intense outflow of liquefied lime-mud, and comparing the observations with the Chinese Seismic Intensity Scale (GB/T17742-2008), the seismic intensity of the experiments was of the order of degrees VIII.

The model box used for the experiments was made of transparent plexiglass, and had a frame of iron at the corners. The sides and the bottom of the soil layers are rigid boundaries with very small deformations, but the top surface of the soil layers is a free deformation boundary. The purpose of the experiments was to observe the overall and particularly the vertical macroscopic and dynamic liquefaction-induced deformations of the soil layers as triggered by the simulated earthquakes. The friction between the lateral end of the layers and the box wall is very small, but does not adsorb boundary waves on the sides of the box. It is preferable to use rubber to form a flexible boundary or to lay a sponge cushion in the surrounding to absorb the boundary waves and reduce the reflection and refraction of the waves at the boundaries (Jing et al., 2004). However, these flexible materials are non-transparent, and even if a transparent observation window is set, it is impossible to observe the developments during the tests completely. Therefore, the soil boundary conditions of this test have obvious advantages and less disadvantages.

4.3 Liquefaction mechanism of the lime-mud with $\leq 5 \mu m$ calcite particles

Calcite particles with grain diameters $\leq 5 \mu m$ are comparable with clay particles, but their plasticity index ($I_p < 10$) is lower, and their properties are similar to liquefiable water-saturated silt, indicating that the cohesion of saturated lime-mud is very low. Clay soil with a high cohesion and a high plasticity index ($I_p > 17$) belongs to typical non-liquefiable soil, for a large number of water molecules are firmly adsorbed by electric charges on clay particles in the pores of the water-saturated clay. The mineral composition of a clay particle is, however, fundamentally different from that of a calcite particle. The former is a clay mineral with electric charges on its surface, and the latter is calcite with rarely electric charges on its surface, so the properties of these two particle types differ greatly. Most water molecules are preserved in lime-mud pores in the form of free water molecules. When water-saturated lime-mud consisting of particles with diameters of $\leq 5 \mu m$ is affected by a strong earthquake, an excess pore-water pressure is generated that is sufficiently high to overcome the effective stress around the pores to make the lime-mud liquefy. Therefore, the fundamental difference between clay particles and micritic calcite particles is neglected in the reference (Meng et al., 2006); excluding the 5–15 $\mu m$ microspar particles from the liquefaction range is not appropriate. As the effective stress around pores becomes larger along with depth, and because lime-mud pores of particles with a diameter of $\leq 5 \mu m$ are too small, it is impossible to generate a sufficiently high excess pore-water pressure at greater depths to overcome the larger effective stress. Therefore, liquefaction only occurred in the shallow part in the case of simulated earthquakes with the same intensity (Fig. 2). Compared with $5\mu m$ diameter calcite particles, the diameters of 10–30 $\mu m$ calcite particles are 2–5 times larger, more specifically the same as those of fine sand (Feng, 2013). Such a large size of calcite grains in a water-saturated lime-mud, makes the liquefaction depth obviously increase if affected by earthquakes with the same intensity (as shown in Fig. 6b), which is easy to understand.

4.4 Explanation of hysteresis and persistence of liquefaction phenomena

The test study showed that macroscopic liquefaction occurred a few seconds after the earthquake, i.e. the liquefaction deformation was a hysteresis phenomenon, which explains why the accumulation of the excess pore-water pressure and the formation of intrusion channels for the liquefied material required only a short time. These tests also showed that the macroscopic liquefaction phenomena lasted for a long time, which is the reason why the formation of veins of liquefied lime-mud and lime-mud volcanoes, which is a dewatering process to carry liquefied particles and consume the excess pore-water pressure, lasted till the excess pore-water pressure had diminished to a certain value. On July 28, 1976, a few minutes after the occurrence of the Tangshan Earthquake ($M_s = 7.8$), the liquefaction-induced formation of ’sand-boils and waterspouts' started, and then was lasting for several hours. These simulation tests described here, the duration of the outflow of liquefied lime-mud volcanoes was consistent with the persistence of liquefied sand volcanoes formed during the violent 1976 earthquake.
4.5 Gravity-induced deformation and relevant deformation structure boundary

Some load, ball-and-pillow and vein-shaped deformation structures formed during the tests will without doubt have originated under the combined action of gravity and the simulated earthquakes. However, these deformation structures were superimposed on, and combined with gravity-induced deformation structures produced before the experiments, and it is hard to distinguish between them. No further analysis is therefore made here of the deformation structures generated by such downward movements. It is also worth mentioning that it took 56 days to create the soil layers in the boxes for these tests. Prior to the earthquake simulation test, each soil layer was subject to gravity for more than 70 days. However, the consolidation degree of each soil layer was relatively low, especially for the cohesive soil layers, resulting in not well defined boundaries of the flame structures and veins. Undoubtedly, these deformation structures record the simulated earthquake.

5 Comparable Field Cases

The earthquake-simulation test of water-saturated lime-mud can explain the genetic mechanism of liquefied deformation structures in carbonate lime-mud triggered by earthquakes. Some actual cases developed in ancient tectonic seismic zones or their vicinity (Fig. 7a) have been studied.

Case 1 is a dolomitic lime-mud volcano (Fig. 7b) in the Mesoproterozoic Wumishan Formation in the Xishan area, western Beijing. The diameter of the volcano is 1.1 m; the crater is complete and 30 cm deep, and the volcanic cone is composed of outflown lime-mud (Su et al., 2014).

Case 2 is a lime-mud volcano (Fig. 7c–d) and a lime-mud crypto-volcano (Fig. 7e) in the Early Cambrian Zhushadong Formation in Linyi, Shandong. The conduit of the crater is connected with the source layer, which consists of liquefied lime-mud (Fig. 7c–d). Under the sedimentary palaeo-surface, a lime-mud crypto-volcano body was present with some flow lines in its lower part, which punctured some conglomeratic sand layers, and some soft thin lime-mud interbeds with mud layers forming an anticline (Fig. 7e; Tian et al., 2013).

Case 3 concerns some lime-mud volcanoes (Fig. 7f) in the Early Triassic Nanlinghu Formation in the northern Chaohu area, Anhui. Many lime-mud craters and volcanic cones are distributed over a single bedding plane (Chi et al., 1999).

Cases 1–3 can be explained on the basis of the the results of the earthquake-simulation experiments with Models 1–3, but the scale and size are different. The planview (Fig. 7b and Fig. 7f) of Cases 1 and 3 are consistent with Figs. 2d, 3d and 4e of the experiments.

Case 4 is a diapir in the Neoproterozoic Hejiayao Formation in the Songshan area on the southern margin of the North China Plate (Fig. 7g). Its core consists, like the cone, of outflown liquefied lime-mud that captured muddy masses (Fig. 7g–i) (Feng, 2013). The diapir is associated with veins of liquefied microsparite (molar tooth structure) (Gao and Liu, 2005). This phenomenon is consistent with the experimental results shown in Figs. 3e and 4b.

Case 5 regards veins of liquefied microsparite (micritic calcite) that puncture laminared marlstone of the Neoproterozoic Shiwangzhuang Formation at the Luoma Hill in the southern Anqiu area, Shandong. The veins are connected with a lime-mud layer (the source layer, which became liquefied), which basically is with the same as the lime-mud veins in Fig. 4c; the difference is the cohesive soil without lamination, so that it is impossible to distinguish between the puncturing of the bed and its simultaneous bending.

Other soft-sediment deformation structures generated in earthquake-simulation tests are also common in the strata (Qiao et al., 1994; Failchild and Song, 1997; Pratt, 1998; Qiao and Gao, 2000; Du et al., 2001; Qiao et al., 2002; Gao and Liu, 2005; Qiao et al., 2007; Chi et al., 1999; Tian et al., 2013; Su et al., 2014; Goly and Pandey, 2014). Due to the limited space available here, they are not detailed any further.

6 Conclusions

(1) This study first verified that strong earthquakes may cause violent liquefaction of saturated lime-mud composed of micron-sized calcite particles. The liquefaction led to the formation of lime-mud volcanoes, diapir structures, veinlike structures, curls, micro-fractures and other soft-sediment deformation structures; at the same time intercalated layers of water-saturated cohesive soil developed thixotropic deformation and filling of the seismically-induced microfractures to form muddy thixotropic veins. Part of the cohesive soil was captured by the liquefied lime-mud to form muddy xenoliths.

(2) It appears that liquefaction of water-saturated lime-mud is characterised by the following rule: at a specific earthquake intensity, the depth and the intensity of the liquefaction become larger with increasing particle size of the calcite in the lime-mud. The reason why water-saturated lime-mud composed of calcite particles with grain diameters of ≤ 5–30 μm may induces liquefaction under the influence of a strong earthquake, is its low plasticity index, in combination with the cohesion of the lime-mud. The limited electric charge on the surface of...
Fig. 7. Earthquake-induced lime-mud volcanoes and other liquefaction-induced deformations in China.
(a), Distribution, geological age and tectonic environment; (b), A Mesoproterozoic (P2) lime-mud volcano, western Beijing (Su et al., 2014); (c), The Early Cambrian (Є1) lime-mud volcanoes in Linyi, Shandong Province (Tian et al., 2013); (d), Sketch of Photo c: ① liquefied lime-mud layer; ② liquefied lime-mud vein; ③ laminated marl with mudstone; ④ lime-mud volcano; ⑤ lime-mud volcano crater; ⑥ lime-mud dam. (e), Lime-mud subvolcano (liquefied diapir, Є1) in Linyi, Shandong (Tian et al., 2013); (f), Early Triassic (T1) lime-mud volcanoes in the northern Chaohu area, Anhui Province (Chi et al., 2009); (g), Liquefied diapir structure in Neoproterozoic (P3) carbonate rocks in the Songshan area, Henan Province (Feng, 2013): ① liquefied cone with some captured mud; ② and ③: the laminated surrounding rock punctured by the liquefied diapir structure; (h), Veins puncturing laminated marl of Neoproterozoic (P3) lime-mud (micritic calcite) in the Anqiu area, Shandong Province: ① vein of liquefied sediment; ② thin layer of liquefied lime-mud (limestone). b and f are bird’s-eye views, the other photos show profiles.
calcite particles (especially of particles less than 5 μm) may be the fundamental reason that the plasticity index and cohesion of lime-mud are smaller than those of cohesive soil or silt.

(3) This study answers an academic question, viz. whether a strong earthquake may trigger liquefaction of a submarine lime-mud; it also provides test data that can explain seismic-related sedimentary events. This is of great importance for reclamation of land from the sea and for the analysis of the foundation stability of marine engineering constructions resting on soft calcium-carbonate layers in the neritic environment.

Can microspar-calcite veins (molar tooth structures) and their associated deformations be caused by earthquakes? Until now, arguments have put forward both in favor and against this possibility (Kuang, 2014). This test study presented here shows that a seismic mechanism is not only possible but even likely. Consequently, the tests have yielded data than unambiguously answer the question.

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