

# Discussion on storm-induced liquefaction of the superficial stratum in the Yellow River subaqueous delta

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**Abstract:** Geological disasters on the superficial seafloor were revealed in geological investigation on the Yellow River subaqueous delta. Combined with dynamic triaxial tests and wave flume experiments, occurring conditions and forming patterns of liquefaction as well as motion of the liquefied soil were explained in this paper. Based on the viewpoint that the geological disasters were formed due to silty soil liquefaction under storm waves, re-stratification issue of the superficial stratum was analyzed. Movement of the liquefied soil agreed with the wave, leading to differentiation of the soil particles. Research issues in respect of geological, environment and engineering of storm-induced liquefaction were also discussed.

**Keywords:** Yellow River subaqueous delta, liquefaction, re-stratification, storm wave action

About 88% of the sediments that the Yellow River carries into the sea were deposited in the subaqueous delta front with 8 km from the coastline towards the sea<sup>[1]</sup>. However, the deposition did not stay stably in the initial accumulation area. The superficial deposit would be eroded, transported and deposited again in other areas under the ocean dynamic forces<sup>[2-4]</sup>. Seabed topography on the Yellow River subaqueous delta (hereinafter called YRSD) changed in the course of reformation by ocean dynamic forces. Different landforms such as erosion, collapse, relic dune or platform, and porphyritic rough seafloor were formed<sup>[4,5]</sup>, developing into geologic hazards, including submarine landslide, silty flow, soft stratum deformation, seabed erosion, delta subsidence et al<sup>[6-8]</sup>.

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Landform-transform districts and occurrence districts for geological hazards such as seabed slide and erosion on the YRSD was well corresponded with areas of strong waves. The subaqueous unstable delta front of the northern Yellow River was coincident with the high wave concentration area, in which exists strong disturbance with complex topography<sup>[9]</sup>. The disturbed stratum of the superficial seafloor in the high wave concentration area was focused on by Sun<sup>[10]</sup>. Soil liquefaction under the action of storm waves was considered the main reason. In order to survey the depth and engineering geological characteristic of the disturbed stratum, the static cone penetration test in combination with the engineering geological drilling and shallow-stratum profiling tests were carried out, and the wave-induced liquefaction was also calculated. In laboratory, flume experiments were conducted on seabed made of clayey silt. Shear slide was shown and disturbed stratum was formed in the local soft area of the silty seabed under wave actions. This disturbed stratum was proved to have similar engineering properties with the disturbed stratum surveyed by Sun<sup>[11,12]</sup>, which was an analytic approach to figure out the creation process of re-stratification.

Combining with existing researches, liquefaction condition of the soil, forming pattern, development process, liquefied soil motion as well as the re-stratification on the stratum of the YRSD were discussed in this article. It was also pointed out that seabed soil liquefaction caused by storm waves should be researched in the fields of geosciences, environment, engineering, and so on.

## 1 Evidence of storm wave on Yellow River subaqueous seabed

System research on unstable topography of the YRSD opened with Sedimentary Dynamics Research Project of Southern Bohai Sea and Yellow River Delta on 1980s. Synchronous sail researches were carried out on the sea by high-resolution sound instrument. Subaqueous landslide system was determined to exist at the slope averages less than  $0.5^\circ$ , and was divided into bottle-neck landslide, shallow displacement sheet landslide, shallow rotation landslide (Fig. 4 in Yang 1994)<sup>[2,6]</sup>. Two superficial sediment disturbances were recognized as moderate disturbed area and severe disturbed area. At the front of the severe disturbed area, two kind of seabed landform types were observed as silty flow gully (located at the east or northeast of the delta, arrayed downhill 100 m - 500 m in width) and collapse (located at the front of the delta with a slope of 0.2 - 0.1 and water depth of 10 m - 13 m) (Fig. 2 and Fig. 7 in Prior D B 1986)<sup>[13,14]</sup>. Recently, disturbed and undisturbed areas in northern submarine of the YRSD had been divided by more advanced SES-96 shallow-stratum profiler made in German, and the subtle structural features within some disturbed areas were shown. Through geological drilling tools, differences in

engineering properties between disturbed and undisturbed strata were obtained<sup>[10,15]</sup>. Storm waves were analyzed to be the reason for the hazards on the YRSD mentioned before, such as landslides, silty flow, collapse, and other disturbances. Through the sediment dynamic equipment buried in the seabed, soil motion was recorded during the storm wave and some of the original landslides were also found to "reactivation"<sup>[16]</sup>.

## 2 Occurrence condition and formation pattern of liquefaction

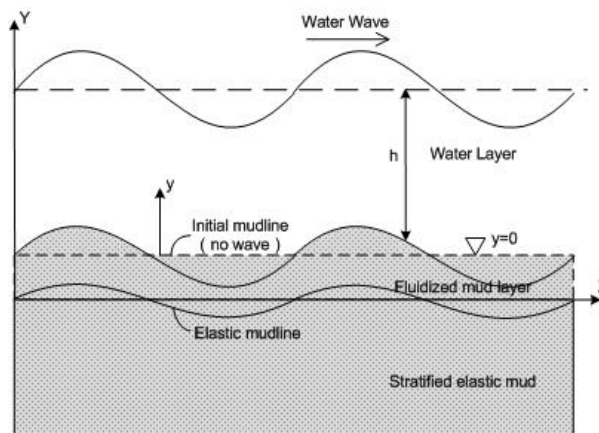
It was formed by the storm waves that unstable topography such as landslides, silty flow, collapse and disturbed stratum were proved to exist on the seabed of the YRSD. What was its initial mechanism? Saturated soil strength was lost under the dynamic action in two forms, namely liquefaction and shear failure. Broad concept of soil liquefaction referred to the liquid state of the soil. However, liquefaction here in the narrow sense means that pore water pressure in the soil was increased under the cyclic loadings till the effective pressure loss.

Cyclical dynamic action was applied to the seabed soil by storm waves. Shear stress was also acted onto the seabed soil by the wave crests and troughs in a wave length range. Consequently, both liquefaction failure and shear failure could happen to the seabed soil.

Seabed soil on the YRSD was not soft mud but with high strength, and its water content was 20% - 30%<sup>[10]</sup>. Combined with flat bottom topography (slope less than 1°), failure of slope under gravity was difficult to form. Only if the wave loading be strong enough would lead to soil failure. This led to the initial state issue when seabed soil damage occurred under wave actions, namely the critical cyclic stress ratio<sup>[17]</sup>. When the ratio of wave loads and soil strength exceeded a critical value, the soil would be unstable.

Particles of silty soil dislocated when dynamic effect of strong waves was acted on the seabed. According to the arrangement of soil particle structures, two cases may occur. One, pore water was difficult to discharge during the particle dislocation, causing the increase of the pore water stress. The other, particles and pore water exchange position, just slide, no significant increase in pore water pressure. The first case was called soil liquefaction issue, in which the principle of effective stress could be applied for explanation. In the second case, the pore water pressure may be increased, but the added value was difficult to achieve the standard of soil liquefaction. As a result, shear failure occurred, while the soil strength was constantly decreasing. In dynamic triaxial tests, failure occurred to silty soil with clay content of 15% or more when pore water pressure increase added to only 60% of the confining pressure<sup>[18]</sup>. This could be shear failure caused by reduce of soil strength under the effect of the silty content, taking thixotropy as its initial mechanism.

According to the comprehensive analysis of the variation of pore water pressure in the flume experiment, relationship between pore pressure and deformation in dynamic triaxial tests, and pore pressure in situ, it was suggested that shear failure occurred on silty soil of the YRSD under the crest-trough action in some cases<sup>[19]</sup>; the seabed liquefaction depth at the water depth of 8.0 m on the YRSD, which was calculated according to the discriminant formula of wave-induced seabed soil liquefaction established previously, was equal to the maximum thickness of the disturbed strata. And it was proved that in some cases the formation of silty soil disturbance was due to soil liquefaction caused by storm wave on the YRSD<sup>[10]</sup>. The superficial strata of the YRSD were consist of silty soil, including clayey silt, silty clay and other types of fine-grained soil. As the strata were composed by different particle distributions and deposited in different historical and environmental dynamics, both liquefaction failure and shear failure had been proved to occur through dynamic triaxial tests and flume experiments<sup>[12,18]</sup>. No matter the initial mechanism was liquefaction or thixotropic, dynamic strength of the silty soil would decay through cyclic loading, and shear movement were likely to occur under the crest-trough wave action. After shear failure, the silty soil was forced to oscillate under the wave action, finally the liquid state of the soil would be shown.



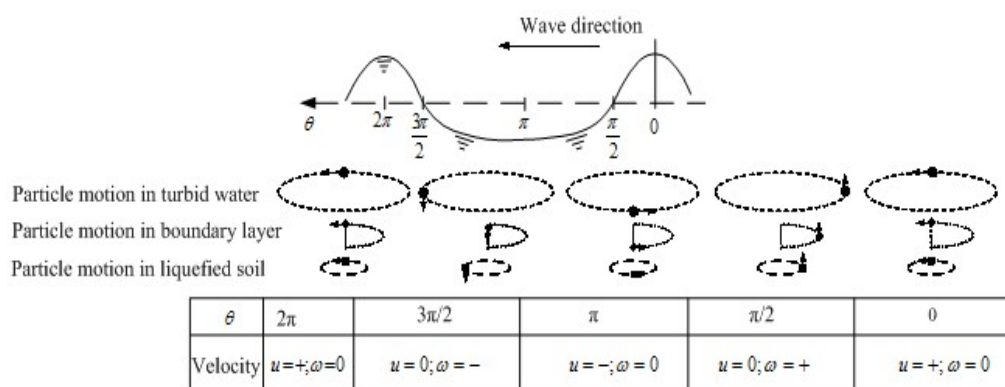
**Fig. 1 Wave Motion of the liquefied seabed Soil**

(According to Foda, et al.<sup>[20]</sup>)

### 3 Movement of the liquefied silty soil

Liquid soil flow on the coastal seabed had similar fluctuation behavior with the upper wave (Fig. 1), while the soil surface was less volatile<sup>[20,21]</sup>. In the flume experiments, liquefied soil with density of  $1.85 \times 10^3 \text{ kg/m}^3$  was observed to have the same wave characteristics with the seabed flow<sup>[12]</sup> During the initial period of fluctuations in the silty

soil, boundary between the upper muddy water and the liquefied soil was not obvious when the sediment concentration of the upper waters (as opposed to the sediment after long volatility) was relatively small. Coordinated movement existed in the two fluids with different density (Fig. 1). The motion of the fluid particle in the muddy water layer and the liquefied soil layer was in uniform pattern. In the circumstance that liquefaction movement fully developed in the silty soil, there appeared a clear boundary layer as fine clay in the liquefied soil constantly oscillated, suspended into the upper water and then enriched between the muddy water layer and the liquefied soil layer. Motion of the fluid particle in the boundary layer was inconsistent with particle motion of either the upper muddy water or the lower liquefied soil (Fig. 2). Different movement patterns of three fluids in various densities were eventually formed.



**Fig. 2 Movement Characteristics of the Liquefied Soil Particles**

(According to Wang<sup>[12]</sup>)

#### 4 Re-stratification of the liquefied silty strata

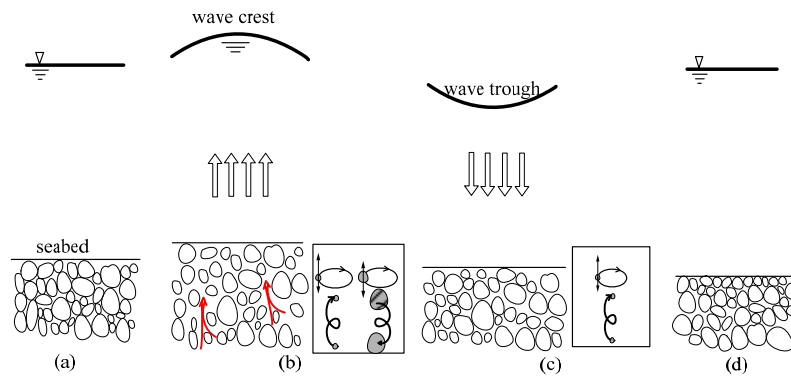
In the wave flume experiments, seabed was made of silty soil on the YRSD. Soil above a certain depth of the seabed was proved in the liquid state. Trajectory of the liquefied soil particle was similar to that of water fluctuation (Fig. 2). It was observed that due to the liquefaction, the original uniform seabed was re-stratified. Soil particles of different sizes differentiated vertically. Due to oscillation and winnowing action of the wave, the finer particles were easy to be suspended in water and move upward with pore water, while the coarser particles oscillate downward (Fig. 3). After the experiments, the liquefied soil were sampled for particle size analysis and cut for the profile observations. The stratification structure with finer particles above and coarser ones below was confirmed to present due to silty liquefaction, as well as parallel bedding, vortex structure and superficial ripple marks, etc. (Fig. 4). Re-stratification occurred when the liquefied silty soil layer

oscillated in situ<sup>[12]</sup>.

Re-stratification in situ caused by silty soil liquefaction could happen in a close place. Collapse pits was formed, and even buried and saved there. Such re-stratification strata could be compared with the wave-induced turbidities described by Zhang<sup>[20]</sup>, which was small scale in an isolated environment. However, when there was a small-angle slope on the seabed, the liquefied soil would oscillate out from the liquefaction position, leading to silt flow described by Prior et al<sup>[13]</sup> or tongue-like dispersed flow mentioned by Yang<sup>[6]</sup>. If shear failure happened on the silt stratum of the superficial seabed under the wave crest and trough, the landslide outer block might appear as described by Yang<sup>[6]</sup> under condition as follows: the fragmentation block did not experience long oscillation; some blocks still existed and overflowed from the liquefaction position and would slide downward along the slope.

### 5 Research issues related to seabed soil liquefaction

Seabed soil liquefaction occurred in the dynamic environment of storm waves. Liquefied strata fluctuate and soil particles were differentiated while the fine-grained soil separated from the formation. As a result, seabed soil liquefaction should be concerned in research fields of geology, environment and engineering, et al.

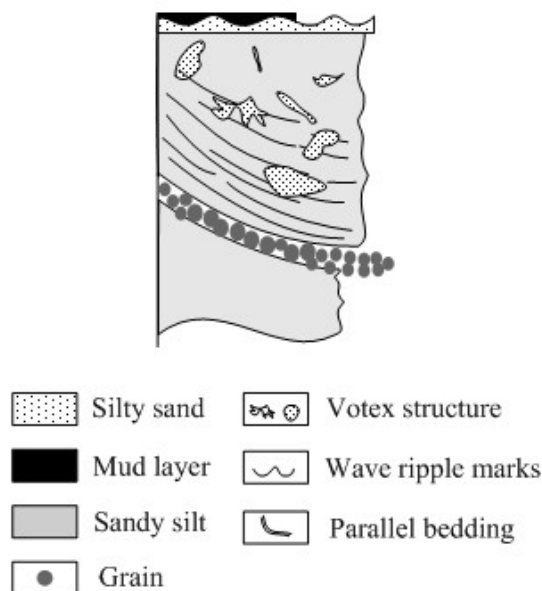


**Fig. 3 Liquefied soil particles divided vertically under waves**

(According to Wang<sup>[12]</sup>)

Geologic research issues: under the action of storm waves, reconstruction of sedimentary strata were caused by seabed liquefaction in situ, forming the positive graded sedimentary sequence. Deposit turbidities could be formed when the liquefied silty soil moved downward along submarine slope. Sedimentary strata caused by wave-induced silty soil liquefaction were relevant to the wave conditions, which provided a basis for wave power inversion by sedimentary strata in storm deposit. Accordingly, interpretive

approaches were put forward for formation, evolution and history environmental analysis of coastal sedimentary structures.



**Fig. 4 Sedimentary structures of In-situ storm deposit**

(According to Xin Wang<sup>[12]</sup>)

Environmental research issues: seabed liquefaction depth on the YRSD reached up to 4.0 m or more, and motion of the liquefied soil led to the precipitation of fine clay soil. Therefore, environmental substances buried in deep strata of the sedimentary history, would be migrated and transformed. Similarly, mass flux would be in unusual amount at the interface between the seabed and the water. As a result, changes of environmental substance flux should be concerned in research on the marine environment.

Engineering research issues: changes of the engineering geology characters were caused by cyclic loading of the storm waves. Damage to structures in shallow sea, sudden siltation in open channel, unusual erosion and other problems were especially induced by soil liquefaction and its movement. Hence, in project security and stability issues, soil liquefaction of the silty seabed should be mentioned as one reason.

## 6 Conclusions

The geological phenomena in the YRSD, such as collapse pits, silt flows, landslides, disturbance strata et al, had been proved to be attributing to dynamic actions of the ocean storm waves. It was summarized in this paper that the results were due to the liquefaction

movement of the superficial strata soil under storm waves.

The liquefaction conditions for silty soil under storm waves could be compared with the relationship of wave load and soil strength, taking the critical cyclic stress ratio as a criterion. Motion pattern of the liquefied silty soil was consistent with that of the wave. Soil particles of different sizes differentiated vertically under winnowing action of the waves. The finer particles moved upward and the coarser ones moved downward. This led to re-stratification of the liquefied strata, forming parallel bedding, vortex structure and superficial ripple marks, et al.

Combined with dynamic triaxial tests and wave flume experiments, occurring conditions, forming patterns, and developing process of liquefaction as well as motion of the liquefied soil and re-stratification issue of the strata were explained in this paper. However, more field data evidences still need to be supplied, may a new understanding be proposed. Based on the viewpoint that the geological disasters were formed due to silty soil liquefaction under storm waves, issues in fields of geological, environment and engineering should be researched, such as the resulting depositional systems and structures, marine geological disasters, the re-migration and transform of the environmental substances into the strata, the effect of soil liquefaction to the suspension sediments, the role of soil liquefaction on the engineering structures, et al.

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## 黄河水下三角洲浅表土体的风暴液化问题探讨

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**摘要:** 黄河水下三角洲的地质勘察揭示了海底浅表地层发生的各种灾害地质现象。本文以风暴浪导致海底土体液化观点, 结合土体动力三轴试验、波浪水槽试验, 对黄河水下三角洲浅表地层土体的液化发生条件、形成模式、液化土体运动以及地层发生的重新层化问题进行了分析, 指出黄河水下三角洲的灾害地质由于风暴浪导致海底粉质土液化运动而形成, 液化后土体运动形式与波浪运动一致, 液化土体运动造成的土颗粒分异而使地层重新层化, 并初步指出了风暴浪导致海底土体液化在地学、环境、工程等方面的研究问题。

**关键词:** 黄河水下三角洲; 液化; 重新层化; 风暴浪作用