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DETAILED INVESTIGATION OF PILES DAMAGED BY HYOGOKEN NAMBU EARTHQUAKE

Kenichi HORIKOSHI[1], Akira TATEISHI[2] And Hiroyasu OHTSU[3]

SUMMARY

Since the 1995 Hyogoken Nambu earthquake, a number of detailed investigations have been conducted on damage to piles in the reclaimed islands of Kobe. This paper presents the results of a detailed investigation of 111 piles, which were driven more than 10 years ago on one of the reclaimed islands of Kobe. The diameter of the piles varied from 400 mm to 500 mm, and their lengths were 33 m or 36 m. There were two joints along the length of the piles, the upper segment of the piles was made of concrete covered with a steel pipe (SC pile), while the middle and lower segments were made of high strength pre-stressed concrete (PHC pile). Two things to note which were applicable to all 111 piles were:

(1) At the time of the earthquake none of the piles was supporting a superstructure on top. Therefore, the damage to the piles were solely caused by soil during and after the earthquake.

(2) All the piles were driven in the reclaimed island, however the distance from the nearest quay wall, which moved towards the sea about 2 - 4 m, was as far as 350 m. Therefore the effects of such large quay wall displacements were thought to be small.

The methods used in the investigation of damage to the piles were (1) low strain integrity test, (2) visual inspection of pile damage from inside by using a water-proof CCD camera, and (3) pile deflection measured by means of a specially made inclinometer.

The results of the investigation showed that all the piles were significantly damaged at a depth where a reclaimed soil layer existed. A major crack was found in almost all the piles at a depth of about 8 m, i.e. below the boundary between the reclaimed soil layers of coarse sand with gravel and medium sand with gravel. The horizontal residual displacement of the pile top was about 250 - 420 mm. Interestingly, all the pile tops were inclined in the direction of the soil displacement, which was perpendicular to, and not along, the direction of major shaking. It was considered that differences in the dynamic soil responses between the above-mentioned two reclaimed sand layers caused such damage to the piles.

INTRODUCTION

Since the 1995 Hyogoken Nambu Earthquake which struck Kobe city in Japan, a number of detailed investigations on the foundation damage have been reported such as [3],[4] and [6]. It is also well-known that the earthquake caused widespread liquefaction on almost all reclaimed islands in Kobe. Hamada et al [1] examined the distribution of the residual horizontal displacement of the soil, and found that soil near the waterfront lines moved by as much as 2 - 4 m towards the sea.

[1] *Taisei Research Institute, Taisei Corporation, Yokohama, Japan Email:kenichi.horikoshi@sakura.taisei.co.jp*
[2] *Civil Engineering Design Section, Taisei Corporation, Tokyo, Japan Email: tateishi@ce.taisei.co.jp*
[3] *Civil Engineering Department, Kyoto University, Kyoto, Japan Email: ohtsu@geotech.kuciv.kyoto-u.ac.jp*

The investigations revealed that many piles in the liquefied soil suffered significant damages due to the effects of the earthquake. It, also, appears that the damage to piles was more pronounced near the waterfront possibly due to the large residual displacement of the quay walls.

This paper presents the results of a detailed investigation of 111 slender piles damaged by the Hyogoken Nambu earthquake on one of the reclaimed islands, Fukae Hama, in the east part of Kobe city. As mentioned earlier there was no superstructure and footing on any of the pile tops at the time of the earthquake. Therefore, the piles were considered to be damaged only due to the effects of soil displacement related to liquefaction. Also, the nearest distance from the quay walls to the piles was as at least 350 m so that the effects of the large quay wall displacements were considered to be small.

OUTLINE OF THE INVESTIGATION SITE

The reclaimed island where the site was located suffered from significant liquefaction during and after the Hyogoken Nambu earthquake. The authors investigated the distribution of crack width which surfaced on the ground with distance from the waterfront line, as shown in Figure 1. According to the figure, the crack width was large within a distance up to 150 m from the waterfront line. As the piles were at least 350 m from the quay walls it was therefore considered that the effects of the large quay wall displacements on the pile response at this site was small. Hamada et al.[1] reported that the soil at the site moved by about 1 m in the south-west direction based on analyses of aerial photographs before and after the earthquake.

Figure 2 shows an overview of the investigation site. In the photograph, the pile tops are below the soil surface at a depth of about 1 - 2 m in the area where excavated soil can be seen. The excavation was conducted to expose the pile top which was necessary for conducting the investigation.

Figure 3 shows a close-up photograph of one of the pile tops. In the photograph, a small hole can be seen close to the pile surface which was thought to be the result of soil liquefaction. The ground at the investigated area settled by about 0.4 - 0.5 m due to the soil liquefaction. Figure 4 illustrates the settlement.

GROUND AND PILE CONDITIONS

The distribution of the soil profiles with depth was investigated after the earthquake at a point close to pile No. 200 (see Figure 7), and it is summarized in Figure 5. The soil profiles are shown up to a depth of 50.3 m below the soil surface. PS-logging was, also, conducted to investigate the shear wave velocity profile.

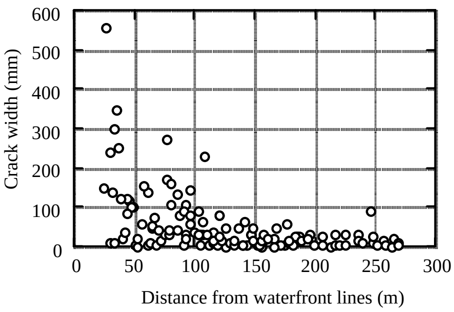


Figure 1: Distribution of crack width observed at the island

Figure 2: Photograph of the investigation site in Kobe.

Figure 3: Hole found near pile surface

Figure 4: Settlement of the fence near the site

In Figure 5, the ground up to a depth of about 13 m below the surface is reclaimed soil which is called 'Masado' (consisting of decomposed granite). The reclaimed soil at the site consists of three layers, i.e. gravel at the soil surface, medium sand with gravel and coarse sand with gravel, and their SPT *N* values and the shear wave velocities are slightly different. It should be noted that there was a slight change in SPT values and shear wave velocity at the boundary between the medium sand with gravel and coarse sand with gravel. The ground water level was at about 2.25 m below the soil surface.

The F_L value, i.e. liquefaction safety factor, was estimated from the soil profiles based on the Japanese Standard for Highway Bridges [2]. In the estimation, the correction factor for area, c_z, was assumed to be unity, and the seismic intensity for the ground was set at k_{hc} = 0.6. The calculated distribution of the F_L value is shown in Figure 6 together with other soil profiles such as mean grain size and fine contents. The results show that the F_L values were below 0.5 throughout most of the reclaimed soil.

The total number of investigated piles was as many as 111, all of which were driven more than 10 years ago.

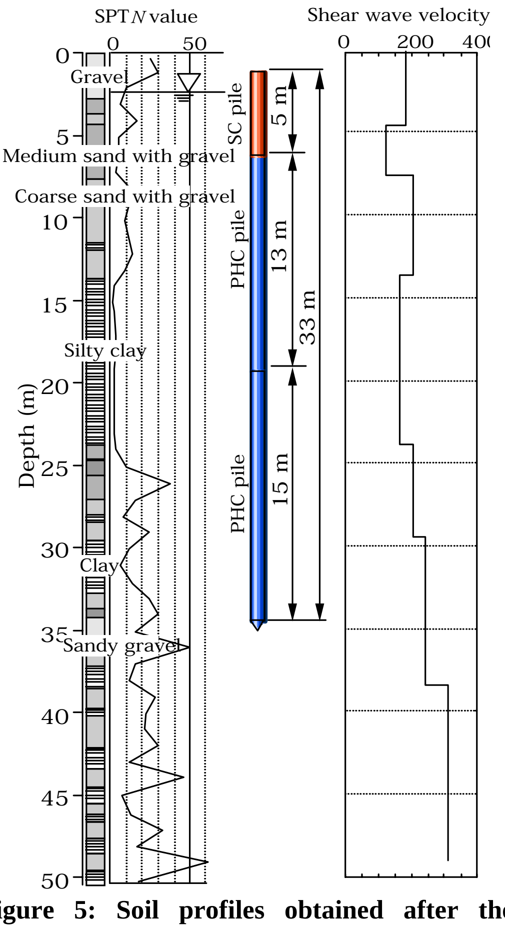


Figure 5: Soil profiles obtained after the earthquake

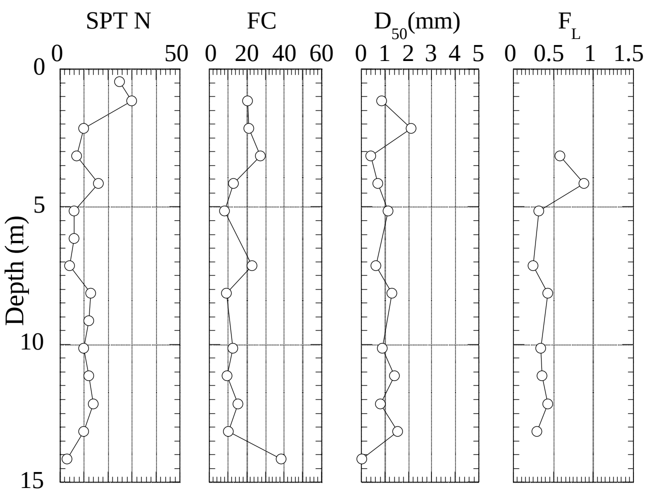


Figure 6: F_L value estimated from soil profiles

Figure 7 shows a plan of the pile arrangement at the site.

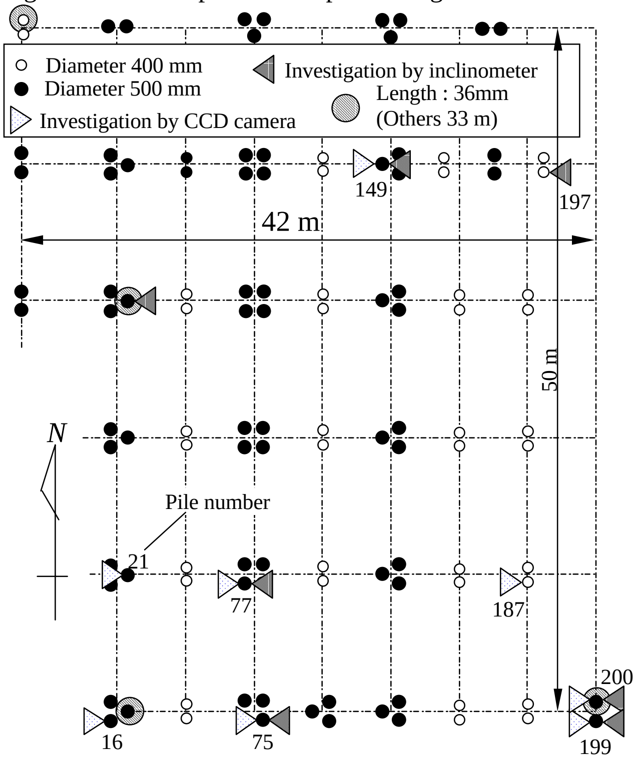
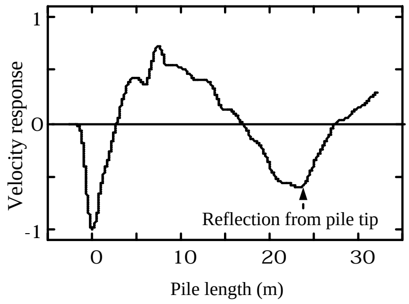
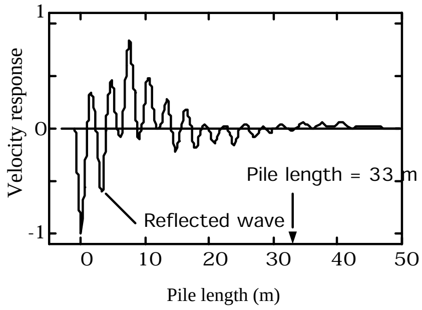


Figure 7: Plan of pile arrangements and investigation



(a) Result from undamaged pile of the same type



(b) Typical result obtained from the pile at the site

Figure 8: Results obtained from low strain integrity tests

The outside diameter of the piles was either 400 mm or 500 mm, and the inside diameter of the piles was 200 mm and 315 mm, respectively. The length of the piles was either 33 m or 36 m (see Figure 7). Each pile had two joints along its length. The upper segment of the pile is the so called SC pile, concrete pile covered by steel pipe and the middle and the lower segments are pre-stressed concrete piles (PHC piles). The tips of the piles were shaped as pencil tops and thud the pile tips were closed.

RESULTS OF INVESTIGATION]

Pile integrity tests:

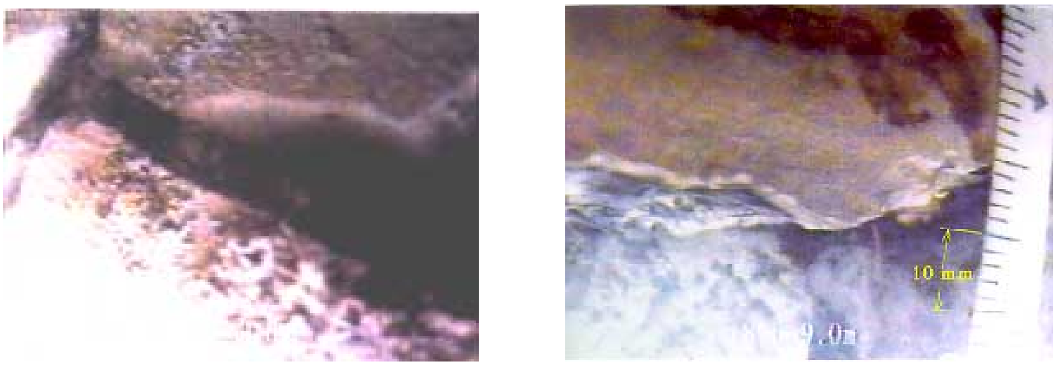
Firstly, low strain integrity tests were conducted for all 111 piles. In the tests, the response of reflected elastic wave from pile tip or the damaged section is analyzed to evaluate the pile integrity. A small impact was applied to the pile top by using a small plastic hammer. The reflected waves were measured by a small accelerometer with a high resolution.

Figure 8(a) shows the result of the integrity test conducted on an undamaged pile which has the same components as the piles examined in this study. In the figure, the horizontal axis corresponds to the pile length, and the depth at which the incident waves are reflected is shown. According to the figure, a clear reflection can be seen at a depth of 24 m, which corresponds to the pile length. On the other hand, Figure 8(b) shows a typical response obtained from the piles at the investigation site. According to the figure, only a reflection from the relatively shallow depth of about 5 m can be obtained, and no reflection from a depth corresponding to the pile length, i.e. 33 m, can be seen. The results obtained from all the piles were essentially the same as shown in Figure 8(b). Therefore, based on the integrity tests it was considered that the majority of the piles at the site might have some damage similar to that depicted in Figure 8(b).

Investigation by CCD camera:

A small water-proof camera was installed inside the hollow pile to visually investigate the damage. The camera used in the investigation had a capability to rotate around its vertical axis with the help of a remote control. The total number of piles investigated by the CCD camera was 8 (see Figure 7). An effort was made to remove as much water and soil inside each pile as possible by using a vacuum. However, in reality, ground water entered into the pile from the outside immediately after the removal probably through the cracks as shown later.

The photographs of major damage taken by the CCD camera are shown in Figure 9 for the piles No. 75 and No. 199. Although it was rather difficult to quantify the crack size accurately from these photographs, it was



(a) Pile No 75, depth about 8 m (b) Pile No. 199, depth about 8.5-9.0m

Figure 9: Pile damage observed by a CCD camera from inside

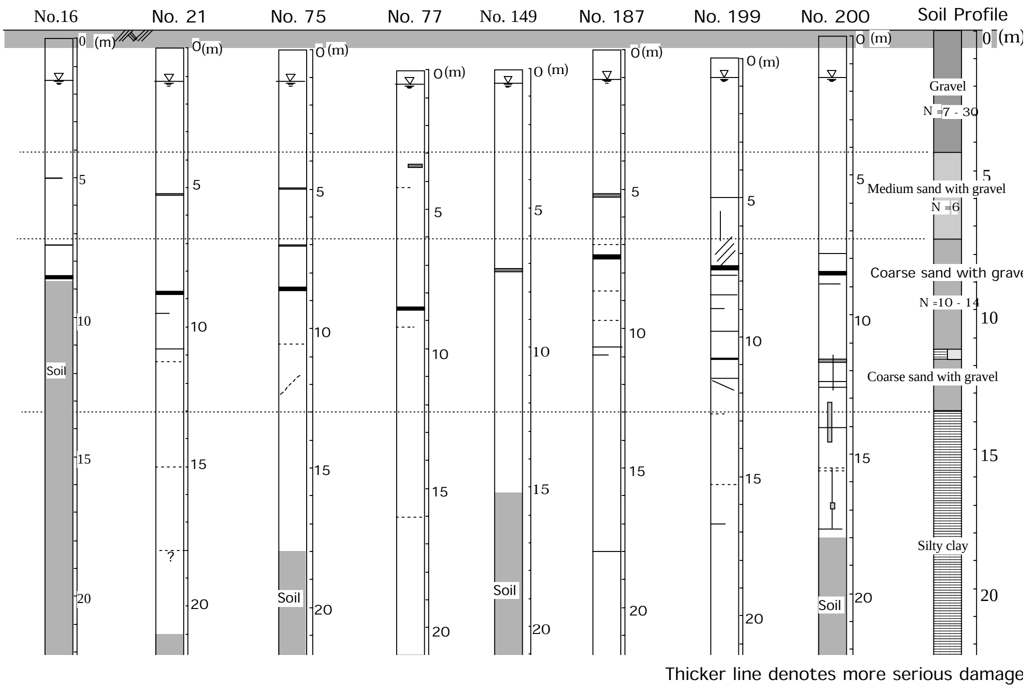


Figure 10 : Summary of pile damage obtained from inspection by CCD camera

possible to estimate the size by making comparisons with the size of the scale shown in the photograph. The actual width of the scale shown in the photograph was 10 mm.

Figure 10 summarizes the findings of this investigation. In the figure, the thickness of the lines represents the size of the crack and the thicker the line the larger the crack. According to the figure, it can be seen that the integrity tests only found the shallowest damage. Large cracks were found in all the investigated piles indicating the severity of damage caused by the Hyogoken Nambu earthquake. The color of the crack as indicated by the photographs taken by the CCD camera was light gray, indicating that the cracks were created just before the investigation, i.e. at the time of the earthquake. At times the inside diameter of the damaged point was sometimes too narrow for maneuvering the CCD camera. The depth of the largest crack in all of the 8 piles investigated using the CCD camera was about 7 - 8 m from the soil surface, slightly below the boundary between the reclaimed soil layers of coarse sand with gravel and the medium sand with gravel.

Investigation by inclinometer:

The depths at which pile damage occurred were estimated from the two tests described above, and in the third series of test the pile deflection was investigated using a specially made inclinometer. The inclinometer used in the investigation is shown in Figure 11, and it is of the same type as the one used by Shamoto et al.[5]. The inclinometer has a capability by which it can be installed on the inside of the pile wall by means of plate springs.

Figure 11: Inclinometer used for investigation

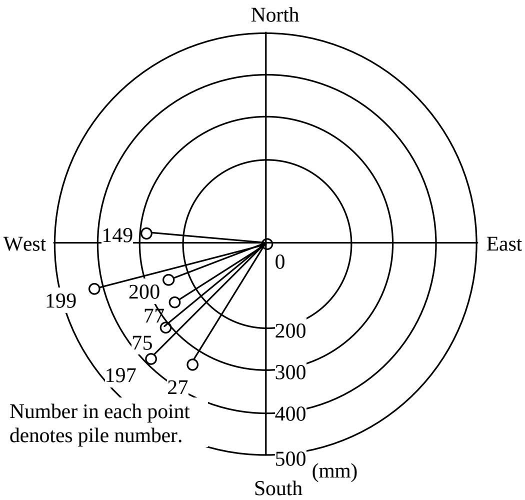
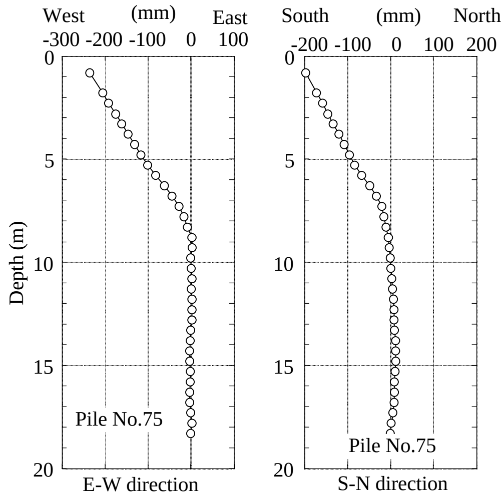


Figure 13: Displacement of each pile top estimated from results of inclinometer

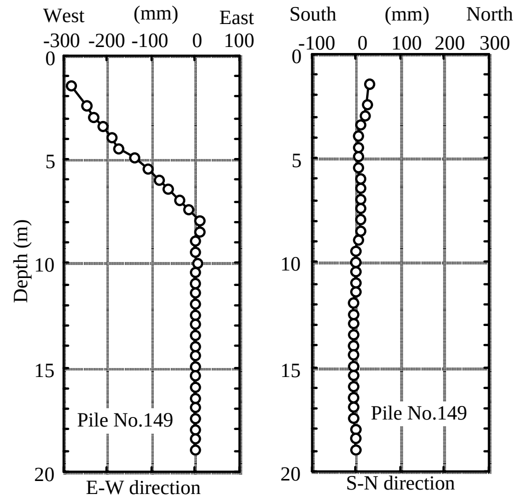
The inclination of the pile was measured at every 500 mm spacing along the length of the pile. A total number of 7 piles were investigated by the inclinometer (see Figure 7).

The pile deflections computed using the inclinometer readings have been summarized in Figure 12. Note that the point of zero deflection was taken at the deepest measured point, and that a correction was made to exclude the initial inclination of the piles occurring from the time of the installation. Since the pile tips are pencil shaped and they were driven into the soil, some inclination at the time of the installation was unavoidable.
The figures clearly show that the piles deflected at a depth about 8-10 m from the pile top. Although the deflection patterns are almost the same for the investigated piles, it was also seen that some piles (pile No. 199 & 200) deflected at two depths. The lower depth of the large deflection was about 12 m from the pile top as shown in Figure 12 (c).

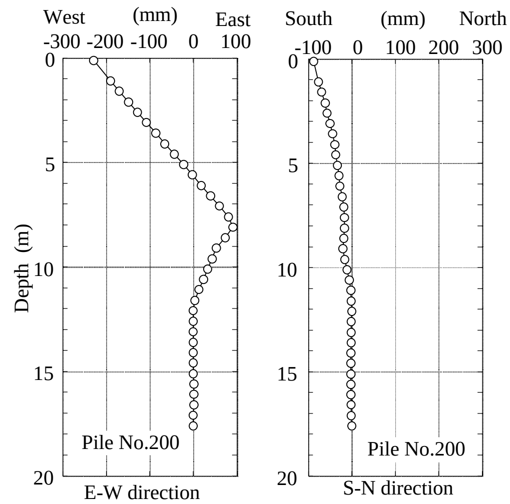
Figure 13 summarizes the direction of the pile deflection. The figure shows that all the piles deflected towards the



(a) Pile No. 75



(b) Pile No. 149



(c): Pile No. 200

Figure 12: Pile deflections obtained from inclinometer

southwest in the direction of the soil displacement as shown by Hamada et al [1]. The magnitude of the pile top displacement varied from 250 mm to 420 mm and was smaller than the amount shown by Hamada et al. It should, also, be noted that the major direction of the shaking in the Hyogoken Nambu earthquake was from the northwest to the southeast. The direction of the pile deflection was perpendicular to the direction of main shaking.

CONCLUSIONS

The results of a detailed investigation of 111 piles which were considered to be damaged due to the effects of soil displacement during and after the 1995 Hyogoken Nambu earthquake were reported in this paper. The findings of the investigation are:

1. Although not a single pile had a superstructure or footing above the pile at the time of the earthquake, significant damage was found in all the investigated piles.

2. The location of the damage was in all cases below the boundary between the reclaimed layers of coarse sand with gravel and medium sand with gravel. The two types of reclaimed soil are referred to as “Masado”, i.e. decomposed granite. The differences in the seismic responses of the two soil layers may have been the cause of such significant damage to the slender piles.

3. The displacements of all the pile tops were in the southwest direction, and they were in the same as the direction of the reported residual soil displacement based on an aerial photographic survey. Interestingly, the direction of the displacements was perpendicular to the direction of main shaking which was in direction of the northwest to the southeast.

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