STUDY ON THE BEHAVIOR OF AN LNG TANK FOUNDATION UNDER THE ULTIMATE LIMIT STATE USING A DEMOLISHED TANK

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ABSTRACT

Robustness of LNG facilities during operation and earthquake is essential for stable energy supply and safety assurance in LNG terminals. Especially, maintaining performance of a foundation has great significance for large-scale and important structures such as LNG storage tanks. Therefore, when demolishing a LNG storage tank (capacity: 45,000m3) after 40 years operation, we executed a lateral loading test using the foundation of this tank in order to verify practical bearing resistance and rupture process of the foundation. The foundation of the demolished tank consists of a concrete base slab with a diameter of 48 meters and approximately 500 steel pipe piles with a length of 25 meters, with a diameter of 406.4mm and with a thickness of 12.7mm. Test pile group and reaction-pile group are set up from the demolished tank foundation. Test pile group, which consists of a concrete slab 15 meters square and a 63-pile group in a 7x9 configuration, was laterally loaded to the point of yield behavior. This test pile group is the world's largest as an in-situ load tests. Strain and rotation angle of piles were monitored by strain gauges and tilt sensors which were installed at external surfaces of piles, and the analytical model was established which can evaluate behavior the performance under ultimate limit state. This paper describes the test results and the evaluation of behavior of LNG tank foundation as well as the established analytical model.

1. INTRODUCTION

Regarding facilities in LNG terminals, structural stability is absolutely imperative for retaining stable energy supply and guaranteeing safety both during normal operation and in case of earthquake. In particular, maintaining the bearing capacity of the “foundation” is an essential point. Above all, the appropriate foundation performance should be guaranteed that can support important large-scale structures such as LNG tanks from the aspects of secure operation and maintenance.

Recently, we removed LNG tanks that had been in service for over 40 years. Making the most of the demolition, we conducted a load test on an actual tank foundation in order to examine the actual bearing strength of the foundation against horizontal force, the damage condition and the behavior of the foundation as a pile group.

The LNG tank foundation on which the test was executed consisted of a base slab, 48 m in diameter and 0.8m in height, together with a total of 496 steel pipe piles, each of 25 m long, 406.4 mm in diameter, and 12.7 mm thick. The test pile group and the reaction block were formed from this foundation. The test pile group consisted of a total of 63 piles in a 7 × 9 matrix, and loaded to yield zone. This test was the in-situ largest in-situ horizontal loading test that had ever been carried out.
Strain and rotation angle were measured at the head of piles by using strain gauges and inclinometers installed on the surface of piles. Then, the load distribution among piles was calculated from measurement results to determine the behavior of tank foundation with the pile group.

This document reports the summary and the test results for the LNG tank foundation.

2. PURPOSE OF TEST

2.1 Background and Purpose

LNG tanks are large-scale and important structures intended for storing flammable substances. It is required that the LNG tank foundation should have the bearing force to withstand not only the vertical load of a tank and LNG in operation but also the horizontal load due to the inertia force at the time of earthquakes.

The LNG tank foundation is a group pile foundation that contains an unprecedentedly large number of piles compared to other structures. Conventionally, the behavioral characteristics of the support mechanism of a group pile foundation have been evaluated according to model experiments, some actual foundation tests and analyses. However, some aspects of behavior of large-scale pile groups remain unclear because it is difficult to examine the horizontal behavior of a large-scale group pile foundation using an actual group pile.

Recently, Osaka Gas decided to demolish LNG tanks that had been used for more than 40 years at Senboku LNG Receiving Terminal 1 (Figure 1). This provided an opportunity to execute a horizontal loading test on an actual larger-scale pile group consisting of 63 piles than ever before. This made it possible to examine the actual bearing strength against horizontal forces of a foundation that had been in service for a long period of time. Also, the test pile group could be loaded to large displacement because the foundation was to be removed after the test. Therefore, yield behavior and rupture situation could be investigated under the ultimate state.

2.2 Structure of Existing Tanks

The demolished LNG tank was a double-walled metal tank with a capacity of 45,000 m$^3$ (Figure 2). The foundation consisted of base slab and foundation piles driven into the ground beneath the slab. The base slab was made of reinforced concrete and was discoid shape as shown in Figure 3; 48 m in diameter and 0.8 in height. The foundation piles consisted of steel pipe piles, each of which was 25 m long and had an O.D. of 406.4 mm. The thickness of the upper part of the pile was 12.7 mm, and that of the lower part of the pile was 9.5 mm. A total of 496 piles supporting tank and base slab protruded from 0.8m above the ground surface. In
order to increase the rigidity of the piles, the top 6.0 m of each pile had been filled with reinforced concrete.

Figure 2. Double-walled metal tank

Figure 3. Base slab after demolition of double-walled metal tank
Figure 4. Specification of tank foundation and framing plan of piles

Diameter of base slab: 48m

Steel pipe pile
Length: 25m
Diameter: 406.4mm
Thickness: (Upper part) 12.7mm
(Lower part) 9.5mm
Number: 496

Figure 5. Details of pile head

Base slab
Protection
Filled with reinforced
Steel pipe
3. TEST PLAN

3.1 Test Pile Group (test pile group, reaction block, loading equipment)

Prior to executing the test, a test pile group and a reaction block were made from the base slab as shown in Figure 6 and Figure 7. The test pile group consisted of a total of 63 piles in a $7 \times 9$ matrix cut out from the foundation. In order to support the reaction force of the jacks used to apply the load, the reaction block was composed of remaining half of the piles and concrete foundation.

The maximum load applied to the 63-pile test pile group was set to 30,000kN, which is approximately twice the design yield load of 15,500kN. The loading equipment consisted of six dual series-connected 5,000kN hydraulic jacks arranged in a transverse row, to enable a major displacement of up to 40cm.
3.2 Loading Plan

The horizontal loading test was executed using the stage loading method. The 63-pile test pile group was loaded in six stages from an initial cycle of 4,000kN, followed by 8,000kN, 12,000kN, 16,000kN, 20,000kN, and 30,000kN.

4. TEST RESULTS

Figure 11 shows the relationship between the load applied to the 63-pile test pile group and the displacement of the base slab.

During the stage loading toward 30,000kN in the final cycle, which is almost twice the design yield load of 15,500kN, the displacement of the piles increased at the point where the load reached 25,400kN (403kN/pile). The horizontal load test was terminated here because we assessed that this was the maximum limit of load on the piles. This result indicates that the ultimate load on the 63-test piles is 25,400kN; 1.64 times the design yield load 15,500kN. The maximum displacement of the base slab was 265mm with the ultimate loading, and the residual displacement of the base slab of 200mm remained after the load was removed.
Figure 11. Relationship between load and displacement (slab)

Figure 12 shows the relationship between the load and displacement of the center pile in the front row. The result determines that the yield load of the piles in the front row is 16.800kN, because the displacement of the pile increases steeply when the stage loading by jacks crosses over 16,800kN. It is verified that the test result of yield load is almost the same as the design yield load 15,600kN that we estimated for the structural design of tanks.

In addition, it was assured that the entire foundation could maintain horizontal bearing force against the yield load even after the piles in the front row yielded.

Figure 12. Relationship between load and displacement (center pile in front row)

Figure 13 shows the deformation of the leading pile when subjected to the maximum load and Figure 14 shows the damage to the top of the leading pile at the point where it is bonded to the concrete slab, after removal of the load. The cover concrete at the connection between pile and base slab partially broke away, however no serious damage that detracted the supporting performance of foundation against the vertical force of tank was found.
Figure 15 shows the allotment of the load on the piles during each cycle of the stage load application. The result indicates that the load sharing ratio at the front pile is the largest, and it decreases gradually at the middle pile, then at the rear pile. In addition, it is apparent that the more load increases, the more the shared loads on the middle pile and the rear pile decrease in steps.

4.2 Considerations

When a horizontal force acts on a base slab consisting of multiple foundations, the foundation piles are normally designed so that the load is applied equally to each pile. From the results of this test, it was confirmed that the largest load sharing ratio was applied to the front piles, and a lesser ratio was applied to the center and outward piles, and also that the ground between adjacent piles behaved as a single body. The resistance of the ground in front of the piles in the front row increased, which tended to cause the load on the leading piles to increase.
5. CONCLUSION

As a result of the above test, the ability of an actual LNG tank foundation that had been in service for 40 years to resist a horizontal load was confirmed. It was also confirmed that whereas the design yield load of the base slab of the 63-pile test pile group was 15,500kN, the actual bearing strength was 25,400kN, or 1.64 times the design value.

Furthermore, as a result of applying a load until the end condition, the behavior of the foundation and also the nature of the damage to the top of the pile that occurred between the start of yield to the point of major deformation was confirmed. When the end condition was reached, a certain degree of separation of the cover concrete was found at the tops of some of the piles of the LNG tank foundation, but there were no signs of damage that could conceivably impair the bearing performance of the entire foundation. Consequently, it was confirmed that the foundation could reliably bear the load of an LNG tank even when it was subjected to a horizontal load due to inertia in the event of an earthquake. Also, because no harmful cracks were observed in the reinforced concrete foundation, which had been in service for over 40 years, and because no signs of corrosion of the reinforcing bars were observed, the soundness of the foundation as a reinforced concrete structure was also confirmed. Based on these results, it is expected that the design of foundation that supported by multiple piles will be rationalized.