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Verification test for integrity of equipment foundations affected by dynamic load

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1 ABSTRACT

The seismic capacity of anchoring portion of equipment has been an important issue. This report describes the plan and results of seismic tests performed to confirm the structural capacities of anchor bolts and concrete anchoring portion to fasten equipment and pipe supporting systems in concrete structures of nuclear power plants. Three types of seismic tests were carried out, i.e., i) tests in which pull-out forces were loaded to anchor bolts, ii) tests in which shear forces were loaded to anchor bolts, and iii) tests in which observed strong motion were loaded to real scale model. In addition, internal damages and residual strength were surveyed after seismic tests. As a result, it is confirmed that anchor bolts, which are designed in accordance with the existing Japanese design guidelines, have sufficient capacities even after application of dynamic loads.

2 INTRODUCTION

In the design of equipment and pipe supporting systems for nuclear power plants of Japan, anchor bolts embedded in concrete structures are designed to conform with Japan Electric Association's guideline[1)], which were established on the basis of experimental study[2)]. However, the tests were performed under static loads. The capacities of anchor bolts for dynamic loads, therefore, have not been confirmed experimentally. Because the seismic load is one of the dominant loads in the anchor bolt design, it is essential and important to verify the behavior and integrity of concrete anchoring portion for dynamic loads.

In this study, seismic tests of concrete anchoring portion installed in concrete slab of 1m thickness were conducted, and these tests consisted of pull-out loading test, shear force loading test and actual equipment model test. Various models were installed on the same concrete slab on a shake table for the tests, and excited on it at a time. These models were planned to have various bearing capacities including relatively smaller capacity to investigate damage condition at anchoring portion, and shaking force was settled much larger than design acceleration level of nuclear power plants. The observed wave of Niigataken Chuetsu-oki Earthquake in 2007 was applied for actual equipment model test, and integrity of anchoring portion of concrete foundation against the earthquake was verified.

After seismic tests, concrete internal damages and residual pull-out strength were evaluated to confirm the influences on anchorage by dynamic loads.

The above seismic tests were performed in Hyogo Earthquake Engineering Research Center, E-Defense, of National Research Institute for Earth Science and Disaster Prevent.

3 SEISMIC TEST FOR PULL-OUT LOADING

3.1 Test method

Table 1 and Figure 1 through 2 show the specifications of test models. The models consist of base plate with anchor bolts and heavy weight connected with the base plate by a steel pipe. They were designed so that pull-out force worked on anchor bolts by horizontal excitation. Major parameters of the models were anchor bolt diameter and embedment depth. The other parameters were the existence of an additional sleeve for construction use and concrete equipment base of 200mm high. Anchor bolts were installed in concrete foundation of 1m thick, and no rebar was installed around anchor bolts except for those in equipment bases. The material of anchor bolt was SS400 of Japanese Industrial Standard (specified minimum yield stress is 235 N/mm2). Initial fastening force was loaded to each bolt by torque (M16:100N-m, M36:1200N-m). Natural frequencies of models were around 15Hz. Two models with the same parameters were prepared. One was used for pull-out test and another for internal crack investigation after seismic tests.

Input motion was an artificial seismic wave which causes high acceleration response. The time history and response spectrum of the input motion are shown in Fig. 3 and 4.

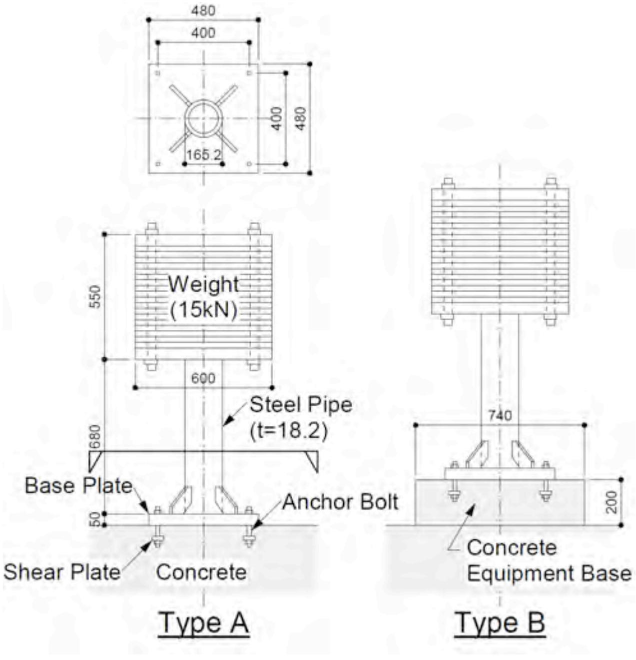


Figure 1. Test model for pull-out loading

Figure 2. Pull-out models on concrete slab

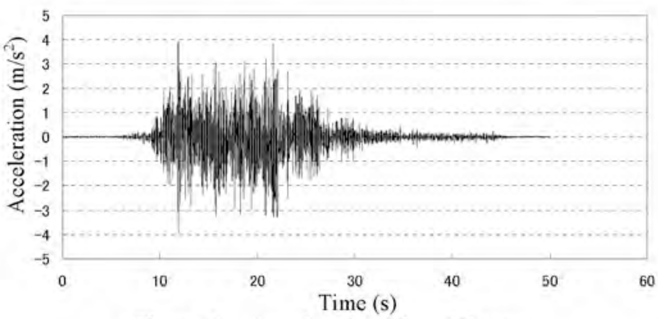


Figure 3. Acceleration time history

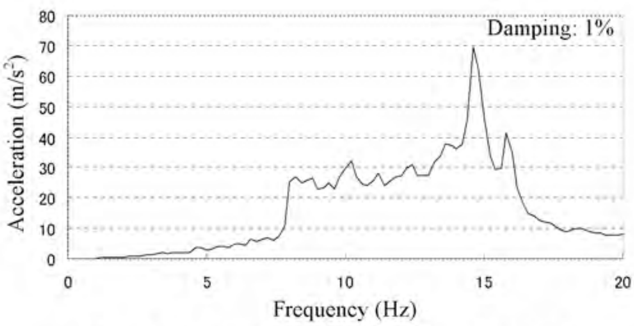


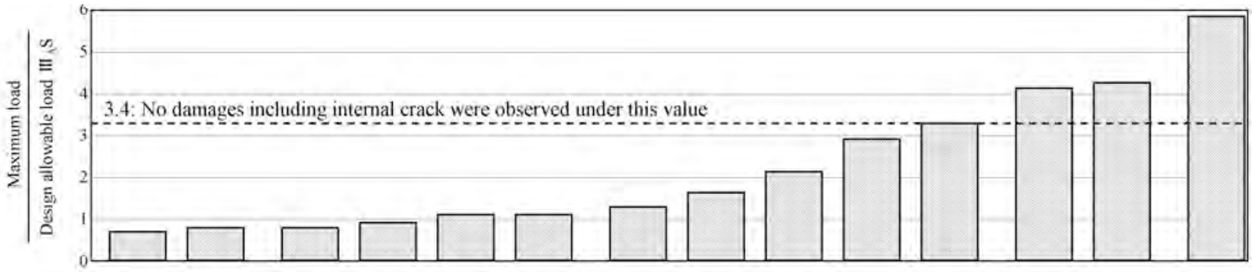
Figure 4. Acceleration response spectrum

Table 1. Specifications of test models and results of seismic and static tests for pull-out loading

No	Bolt	Model type	Parameter			Seismic test		Static pull out test	
			Bolt diameter	Embedment depth (mm)	Shear plate (mm)	Observed Load *1	Internal crack	Observed Load *2	Fracture mode
I-1-1	Standard bolt	TypeA Variable depth	M16	150	80	0.67 0.67		—	Bolt yield
I-1-2				100	80	1.02 1.18		—	Bolt yield
I-1-3				75	80	1.78 1.64		—	Bolt yield
I-1-4				50	50	4.40 4.09	X	1.98	Concrete shear cone failure
I-1-5		TypeA with sleeve		150	80	0.69 0.76		—	Bolt yield
I-1-6		TypeB		150	80	0.62 0.71		—	Bolt yield
I-2-1	Large Diameter bolt	TypeA Variable depth	M36	139	110	1.47 1.09		2.25	Concrete shear cone failure
I-2-2				90	110	2.02 2.11		3.06	Concrete shear cone failure
I-2-3				66	110	3.04 2.93		3.49	Concrete shear cone failure
I-2-4				50	55	6.62 5.93	X	4.10	Concrete shear cone failure
I-2-5		TypeA with sleeve		139	110	1.20 0.96		2.57	Concrete shear cone failure
I-2-6		TypeB		139	110	1.18 1.09		2.29	Concrete shear cone failure
III-1-2	Standard bolt	TypeB large excitation	M16	49	80	3.58 4.87 3.42 4.27		—	Bolt yield

*1 Observed Load = (Maximum load by Maximum acceleration)/(Design allowable load $\mathrm{III}_A\mathrm{S}$)

*2 Observed Load = (Maximum load)/(Design allowable load $\mathrm{III}_A\mathrm{S}$)



No	I-1-1C	I-1-6C	I-1-5C	I-2-5C	I-2-1C	I-2-6C	I-1-2C	I-1-3C	I-2-2C	I-2-3C	III-1-2C	I-1-4C	III-1-2C	I-2-4C
Bolt	M16	M16	M16	M36	M36	M36	M16	M16	M36	M16	M16	M16	M16	M36
Embedment depth	150	150	150	139	139	139	100	75	90	66	49	50	49	50
Model Type	TypeA	TypeB	TypeA with Sleeve	TypeA with Sleeve	TypeA	TypeB	TypeA	TypeA	TypeA	TypeA	TypeB	TypeA	TypeB	TypeA
Internal crack												X		X

Figure 5. Comparison of maximum pull-out force in seismic test and design allowable value

3.2 Seismic test results

Although internal cracks were found in a few models after the seismic test as described in the later section, no surface cracks appeared in any models. Figure 5 shows the ratios of bolt pull-out forces to short term design allowable values (III_AS: $0.45Ac\sqrt{Fc}$, Ac: Effective shear cone area, Fc: Specified compressive strength of concrete). Even though the pull-out forces loaded to many models beyond the design allowable values, no model collapsed by dynamic loads.

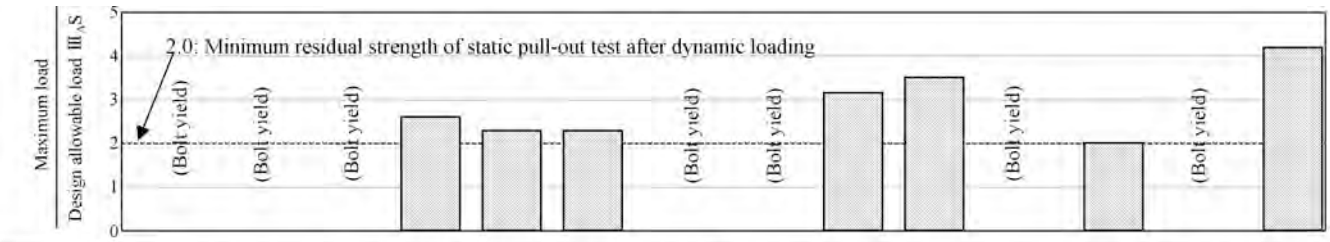
3.3 Internal crack investigation

After the seismic test, concrete around the anchor bolts was cut by core drilling, and their surfaces were visually observed to find internal cracks. A sample of observed internal crack is shown in Fig. 6. Investigation results are summarized in Table 1. It can be found that internal cracks were generated in the models whose ratios of the loaded pull-out forces to the design allowable values were relatively larger. According to the results, the internal crack was found in the model whose pull-out force ratio was 4.1, and no damage could be observed in the model whose ratio did not exceed 3.4.

Figure 6. Internal crack (Model I-1-4)

3.4 Static pull-out test results

Residual pull-out strength was statically tested after seismic test for every model. The test results are listed in Table 1. Major failure mode was the concrete shear cone failure excluding the models which used M16 bolts and had relatively deep embedment depths. The ratios of the residual pull-out strengths to the design allowable values are shown in Figure 7. It can be confirmed that the residual strength satisfactorily exceeds the design allowable value even for the model with internal crack.



No	I-1-1C	I-1-6C	I-1-5C	I-2-5C	I-2-1C	I-2-6C	I-1-2C	I-1-3C	I-2-2C	I-2-3C	III-1-2C	I-1-4C	III-1-2C	I-2-4C
Bolt	M16	M16	M16	M36	M36	M36	M16	M16	M36	M16	M16	M16	M16	M36
Embedment depth	150	150	150	139	139	139	100	75	90	66	49	50	49	50
Model Type	TypeA	TypeB	TypeA with Sleeve	TypeA with Sleeve	TypeA	TypeB	TypeA	TypeA	TypeA	TypeA	TypeB	TypeA	TypeB	TypeA

Figure 7. Comparison of static pull-out strength and design allowable value

4 SESMIC TEST FOR SHEAR LOADING

4.1 Test method

Table 2 and Figure 8 through 9 show the specifications of test models. Anchor bolts were 4-M8(SS400). Major parameter of the models was the shear force loaded to the anchor bolts. Loaded shear forces were settled as the ratios to the design allowable value, i.e., 1.0, 0.5, and 2.0, and weights of models were determined on the basis of these values. The other parameters were the existences of the initial fastening force, sleeve for construction use and concrete equipment base. Anchor bolts were fixed to the base plates of 1600x1600x25mm, and weights were welded on the base plates. Greased stainless steel plates were inserted between the base plates and concrete surfaces to reduce friction and to load shear force from weights to anchor bolts directly. Initial fastening force of each bolt was 12 N-m.

The input motion was determined from the observed strong motion at the Reactor Building (R/B) basemat of Kashiwazaki-Kariwa nuclear power plant unit 1 (KK-1) during the Niigataken Chuetsu-oki Earthquake in 2007. The input motion was amplified to its maximum acceleration of 9.8m/s2 and loaded in one direction.

4.2 Seismic test results

Test results are listed in Table 2. Cut off of the anchor bolt was occured in the model, II-1-4, to which the twice of design allowable shear force was loaded. Although slight pull-out of anchor bolts and flaking of concrete were occurred in tests for pull-out loading, no significant damage which affects the capacities of anchorage could be observed in tests for shear loading.

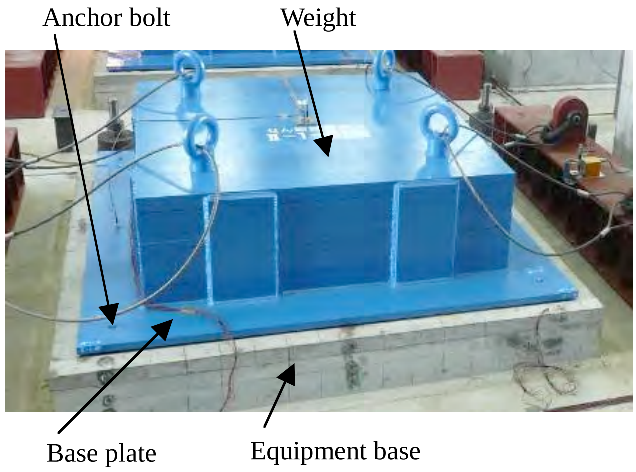


Figure 8. Test model for shear loading (Type B)

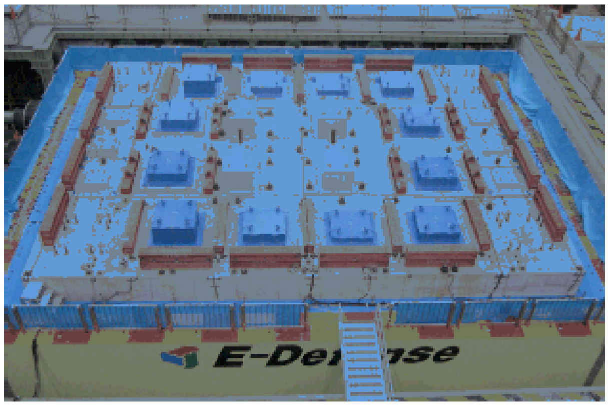


Figure 9. Shear loading model on concrete slab

Table 2. Specification and results of models in seismic test for shear loading

No	Mode Type *1	Bolt diameter	Embedment depth (mm)	Shear plate (mm)	Parameter: Give initial fastening force	Test result: Observed Load *2	Test result: Fracture of anchor portion
Ⅱ-1-1	TypeA Design allowable load III_AS x 1.0	M8	76	40		1.01	
						0.92	
Ⅱ-1-2	TypeA Design allowable load III_AS x 0.5		76	40	X	0.59	
						0.57	
Ⅱ-1-3	TypeA Design allowable load III_AS x 1.0		76	40		1.05	
						0.94	
Ⅱ-1-4	TypeA Design allowable load III_AS x 2.0		76	40		1.91	X
						1.86	X
Ⅱ-1-5	TypeA with sleeve Design allowable load III_AS x 1.0		76	80		0.96	
						1.07	
Ⅱ-1-6	TypeB Design allowable load III_AS x 1.0		150	40		0.94	
						0.96	

*1 TypeA: Without concrete equipment base TypeB: With concrete equipment base

*2 Observed Load = (Maximum load by Maximum acceleration) / (Design allowable load III_AS)

4.3 Internal crack investigation

Figure 10 shows the damages of the model II-1-4 in which anchor bolts were failed in shear. It was observed that the upper half of the anchor bolts were bent and concrete around the bolts was crushed. No internal damages were found in the other models.

II-1-3 II-1-4

II-1-4

Figure 10. Damage of bolt and concrete

4.4 Static pull-out test results

Static pull-out tests were performed for all models except for the model II-1-4, and their failure mode was bolt yielding.

5 SEISMIC TEST FOR REAL SCALE MODEL

5.1 Test method

Representative foundation type was selected among those installed in Kashiwazaki-Kariwa nuclear power plant unit 7 (KK-7: ABWR, 1356MWe) operated by Tokyo Electric Power Company. RHR (Residual Heat Removal System) heat exchanger, which is one of the most important systems, was chosen as the representative model. Figure 11 through 12 show the models fixed on the shaking table. The reinforced concrete block, which has the same weight (about 330 kN) and length with the actual RHR heat exchanger, was installed on two concrete equipment bases by steel supports. One of the steel supports was fixed to the concrete equipment base, and another was connected by the manner that it could be slid in the longitudinal direction. Four M48 anchor bolts were used to fix RHR heat exchanger model to each equipment base. Initial fastening force of anchor bolts was 3 kN-m.

The following three input motions were sequentially applied to the RHR test model in three directions.

1) Observed strong motion at KK-7 R/B basemat during the Niigataken Chuetsu-oki Earthquake in 2007
2) Response at KK-7 R/B basemat for Design Basis Earthquake Ground Motion Ss, declared on May 22, 2008 by Tokyo Electric Power Company
3) 1.7 times the observed strong motion at KK-1 R/B basemat during the Niigataken Chuetsu-oki Earthquake in 2007

5.2 Seismic test results

Figure 13 compares the maximum accelerations observed at the reinforced concrete slab of the test models with the target values of each input motion. It shows that three motions were applied successfully as planned acceleration level. The maximum acceleration reached to 18 m/s^2 which is 2.6 times of the actually observed strong motion at KK-1 in the Niigataken Chuetsu-oki Earthquake in 2007. However, no visual damage could be found on the surfaces of concrete bases and anchor bolts.

5.3 Internal crack investigation

Figure 14 shows the concrete around an anchor bolt cut after three seismic tests. As a result of visual inspections, no significant damage of bolts and surrounding concrete was observed.

5.4 Static pull-out test results

Figure 15 shows the load – bolt pull-out displacement relationship obtained from the static pull-out test. Anchor bolts yielded and extended, and it was confirmed that the concrete anchoring portion maintained pull-resistance beyond the design allowable value even after three times of shaking tests.

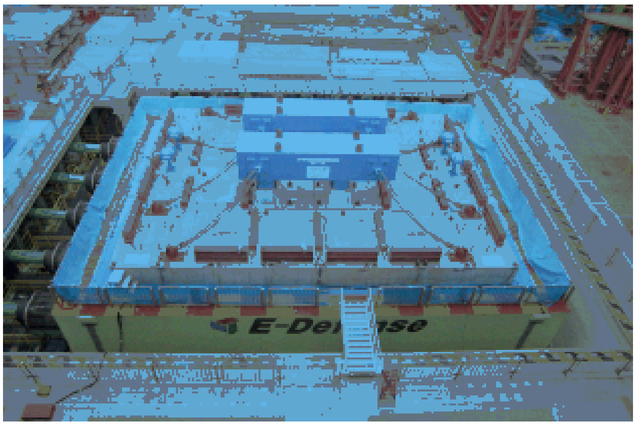
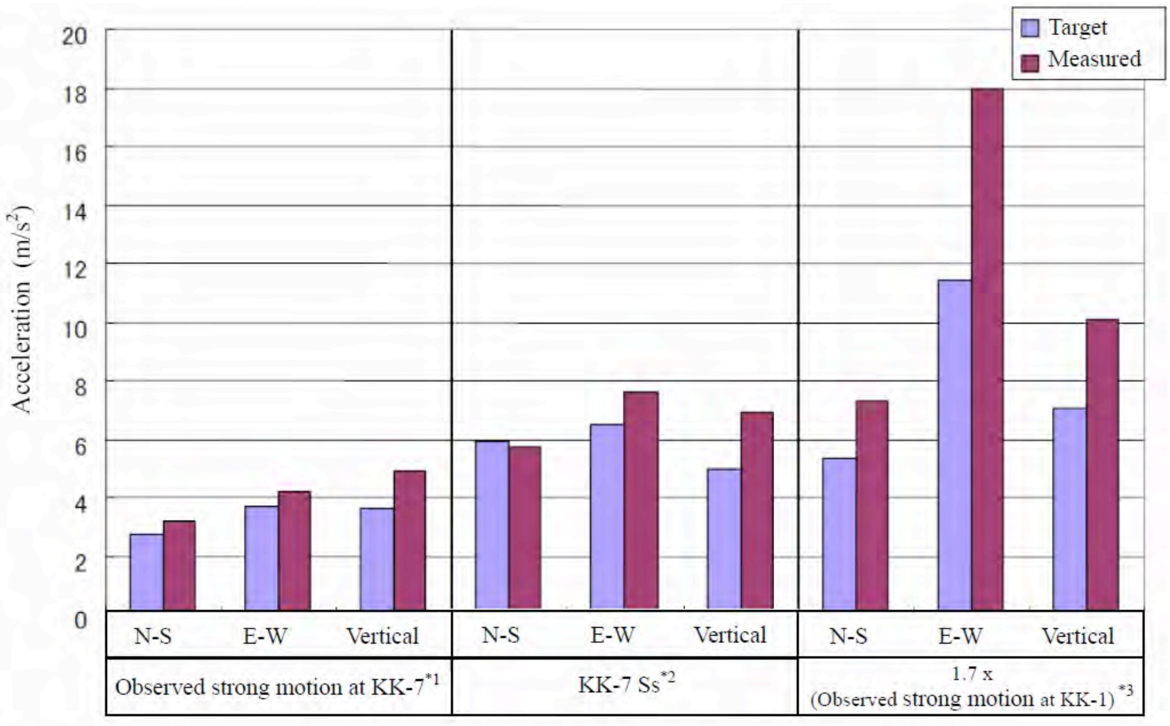


Figure 11. RHR Heat Exchanger model   **Figure 12.** Test models on concrete slab



*1: Observed strong motion at KK-7 R/B basemat during the Niigata ken Chuetsu-oki Earthquake
*2: Response at KK-7 R/B basemat for Design Basis Earthquake Ground Motion, Ss declared on May 22, 2008 by Tokyo Electric Power Company
*3: 1.7 x (Observed strong motion at KK-1 R/B basemat during the Niigataken Chuetsu-oki Earthquake)

Figure 13. Maximum acceleration of input motions

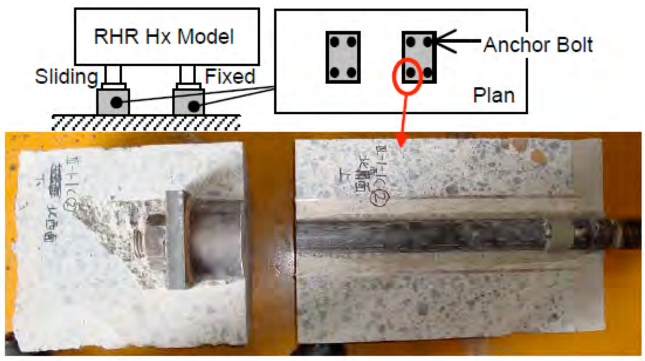


Figure 14. Concrete section around anchor bolt

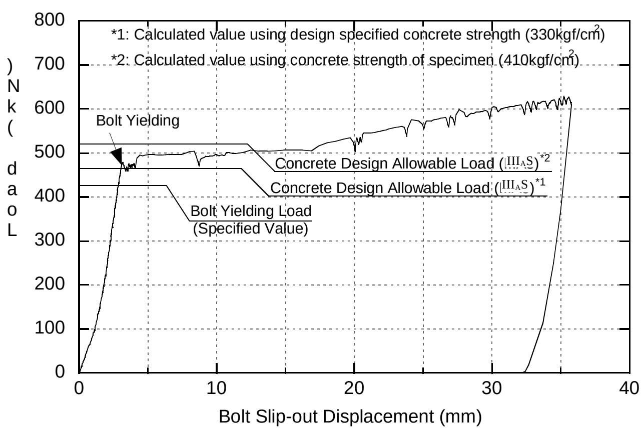


Figure 15. Load – Displacement relationship in static pull-out test

6 CONCLUSION

The following results are obtained from three types of the seismic tests.

- Present seismic design method for the concrete anchorage of equipments and piping system, which is specified in Technical Guidelines for Seismic Design of Nuclear Power Plants, is adequate and has safety margin.
- Residual pull-out strengths of anchor bolts exceed design allowable values even after severe dynamic loads are applied.

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