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Seismic Response of Essential Service Water Pump Considering Nonlinear Behavior of Anchorage

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1. Introduction

Seismic fragility of equipment is essential information for risk assessment of nuclear power plants (NPPs). Equipment in NPPs is normally fixed to the floor with anchor bolts or welding, therefore, the fixed boundary condition(b.c.) is often used for the response analysis when the design basis earthquake occurs. However, for seismic fragility assessment, it is required to analyze the seismic response of equipment under beyond design basis earthquakes, and fixed boundary condition may not give appropriate analytical results. In this research, essential service water (ESW) pump was selected to investigate the seismic response considering nonlinear behavior of anchorage. Nonlinear spring model based on the cyclic loading test is incorporated for support condition in the pump model.

2. Hysteretic Model for Nonlinear Behavior of Anchorage

ESW pump consists of motor(Westinghouse), pump(Ingersoll-Dresser), and supporting anchors as shown in Fig. 1 [1]. The total weight (operating weight including motor and sea water) is about 21.3 ton (46.86 kip) and the natural frequency is about 7Hz.

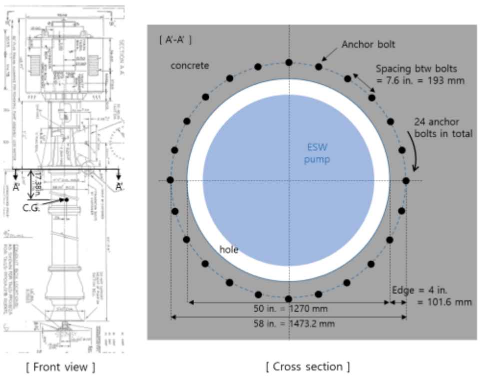
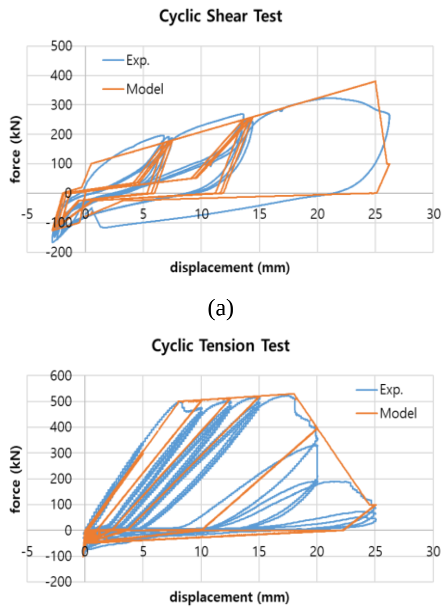


Fig. 1. Front view and cross section of ESW pump

The failure mode of ESW pump is concrete cone failure of anchor according to seismic fragility evaluation report [1]. Tests are planned to identify the cyclic behavior of a single anchor bolt until the concrete failure occurs. Anchor bolt and concrete are prepared to have similar properties with the design documents [1]. The diameter and embedded depth of anchor are 30mm and 316mm, and the compressive strength of concrete is 27MPa (4000 psi).

Experimental results for cyclic shear and tension loading test are blue lines in Fig. 2, and the hysteretic models [2] based on the experiments using OpenSees program are orange lines in Fig. 2. These hysteretic models are applied to the nonlinear spring elements.



(b)

Fig. 2. Experimental results of anchor behavior : (a) cyclic shear test(x-,y-dir.), (b) cyclic tension test(z-dir.)

As shown in Fig. 1, there are 24 anchors around the pump and these anchors should be regarded as group anchor due to the small spacing between anchors. Test results for a single anchor should be adjusted proportional to the projected area for each anchor [3] as shown in Fig. 3.

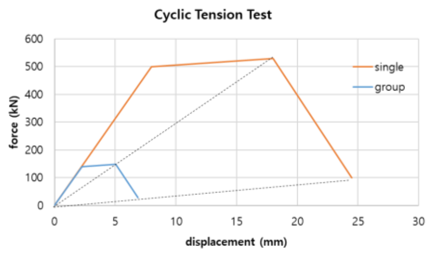


Fig. 3. Comparison of single and group anchor behaviors

3. Seismic Response of ESW Pump

3.1 Ground Motions

The 30 sets of 3D ground motions are generated by using P-Cares program to match the uniform hazard response spectrum (UHRS) at Uljin region in Korea as shown in Fig. 4. ESW pump is located at the elevation of 70ft which is the ground level of ESW intake structure.

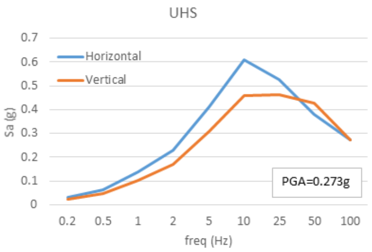


Fig. 4. UHRS for 30 ground motions

3.2 Pump Model for Analysis

The structural model for response analysis is beam stick model consisted of motor, pump, and 24 anchors as shown in Fig. 5. Two horizontal movements at the bottom (node 1) of the pump are restrained [1], and anchors are assumed as rigid elements for modal analysis. Stiffness of beams for motor and pump are assumed to have the first natural frequency of 7Hz. The first five natural frequencies and corresponding mode shapes of the pump model are as shown in Fig. 6.

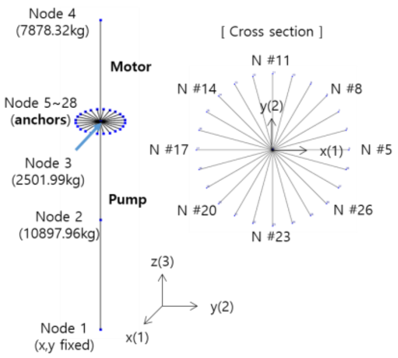


Fig. 5. Structural model of ESW pump

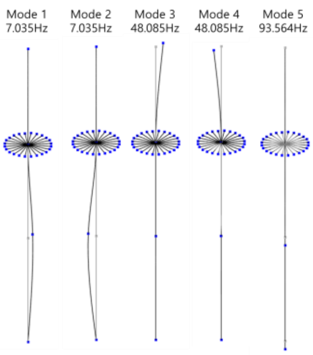


Fig. 6. Natural frequencies and mode shapes

3.3 Seismic Response of Pump

For seismic response analysis, anchors are modelled by nonlinear spring elements with tensile and shear behavior followed by the experimental results in chapter 2. Fig. 7 and Fig. 8 show the time-displacement response and force-displacement relation of one of the anchors, node 8 as marked in cross section of Fig. 5, at a ground motion with PGA=1.7g and 2.6g. As shown in Fig. 7 and Fig. 8, the anchor behavior at PGA=2.6g shows nonlinearity and permanent displacement.

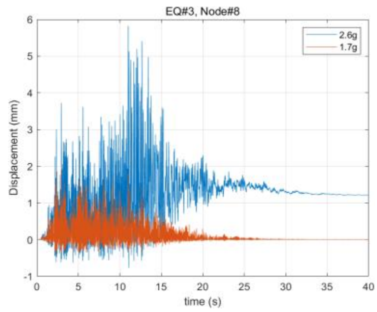


Fig. 7. Time-displacement response of an anchor in z-dir.

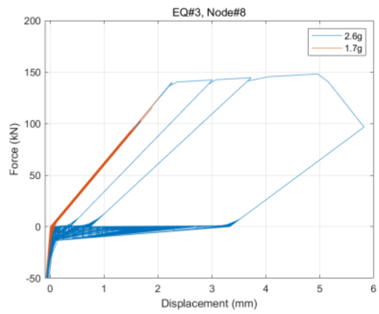


Fig. 8. Force-displacement of an anchor in z-dir.

Fig. 9 shows the time-acceleration response of pump model with fixed b.c. and nonlinear spring b.c. The response is amplified for the spring condition, and the difference between two boundary conditions increases as PGA of ground motions increase as shown in Fig. 10.

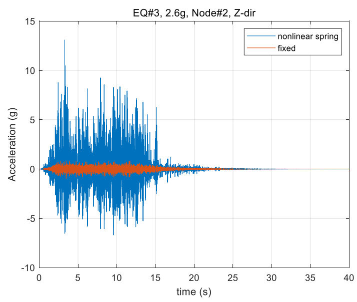


Fig. 9. Time-acceleration response of pump in z-dir. (node 2)

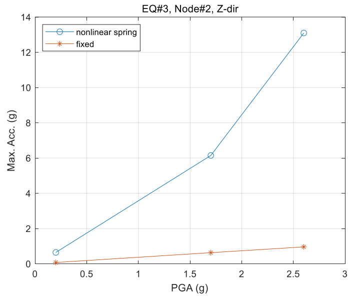


Fig. 10. Spectral acceleration of pump in z-dir. (node 2)

As presented in Fig. 11, the peak frequencies in the response spectrum of pump with spring b.c. are shifted to the lower frequencies. Also, the peak frequency at PGA=2.6g with spring b.c. is slightly lower (about 5Hz) than the others because of the nonlinear behavior of anchors as shown in Fig. 8.

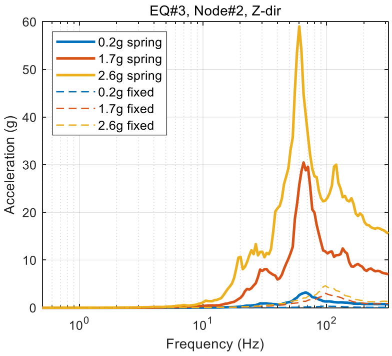


Fig. 10. Response spectrum of pump in z-dir. (node 2)

4. Conclusions

In this research, a simple structural model for ESW pump is constructed considering nonlinear behaviors of anchorage, and seismic response of ESW pump is analyzed. When the seismic load exceeds the elastic limit of the anchor and the defect of anchor occurs, ESW pump shows different seismic response. It is found that elastic model of anchorage has limitations, especially for strong ground motions. This research will be the basis of fragility analysis of ESW pump and risk assessment of NPPs.

ACKNOWLEDGEMENTS

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