A STUDY OF THE INTERACTION BETWEEN THE PIER TYPE WHARF AND CONTAINER CRANE DURING EARTHQUAKES

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SUMMARY

Most of container cranes at Kobe port were damaged during the 1995 Hyogoken-nambu Earthquake, due to the movement of caisson towards sea. Damage of the container cranes was accompanied by uplifting of their legs. In the present state of practice, the design of the container crane and the wharf do not take place at the same time. However, in design, it is necessary to consider the effect of dynamic interaction between them during large earthquake. There are many different types of wharf constructed in Japan, i.e. Caisson type, sheet pile wall type and pier type. The natural period ratio between a pier type wharf and a crane is rather close to 1.0. Also the weight ratio between a pier type wharf and a crane is around 0.5 or higher. The behavior of container crane and pier type wharf during earthquake is affected by the interaction each other. Therefore, in this paper, to investigate the effect of the interaction between the container crane and pier type wharf, we conducted two kind of numerical simulations and carried out an excitation test on a 1/15 reduced scale test model of a container crane and a pier type wharf. We proposed a simple double decked mass-spring model, and a 3-D FEM nonlinear response analysis (using MSC/NASTRAN). The numerical simulation results showed good agreement with the shaking table excitation test results using the 1/15 scale container crane and pier type wharf model.

INTRODUCTION

The reconsideration of the earthquake-proof design method at the harbor facilities which contain a container wharf since the 1995 Hyogoken-nambu earthquake was rapidly carried out. The first stage of design procedure is using pseudo static method, in addition, it is necessary to evaluate the performance of structures during earthquake [Tanabe et al, 1998]. With it, the dynamic analysis technique became introduced by the design codes of the harbor facilities in Japan. The conventional design code treated only the member strength at pseudo static horizontal force applying by kh=0.2. However, the actual damage of container cranes during the 1995 Hyogoken-nambu earthquake caused by the uplifting phenomena of the legs [Kanayama and Kashiwazaki, 1998]. In this way, because the dynamic analysis technique became introduced to the design, the necessity to examine both of the container crane and the wharf behaviors at the same time. That is, as for the design of the wharf and the container crane, the dynamic interaction effect must be considered.

TEST PROCEDURE

2.1 Test models:

Fig.1 shows the global over view of the model and shaking table.
The principal dimension of the test model was determined to be one-fifteenth of the actual structure because of the limitation of the shaking table. Because of the 1G gravity field plays an essential role in the uplifting phenomena, scale ratio of acceleration must be unity. In this test, dimensions of the cross section of the members

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were appended to compensate the reduced weight. Because the elastic motion of this model is dominated by the bending deformation of the members, the axial stiffness does not play an important role [Kashiwazaki and Kanayama, 1996]. Therefore, reduction of the second order moment is almost equivalent to reduction of elastic modulus. Principal scaling relations between the prototype structure and the model are shown in **Table1**. Natural period of the prototype crane is about 2.0s [Yamamoto et al, 1999].

Dimensions of the test model are shown in **Fig.2**. The material of the members is steel; vertical legs were made of prismatic pipes. In this model, JIS class plates and pipes were used. The model had flange joins just above the horizontal members as shown in **Fig.2**. Using the flanges, it is easy to change both of the fixed-leg model and hinged-leg model. Container crane model has wheels. The member of wheels was reduced from eight per one leg in the actual structure to one per one leg to make the model simple. The wheels are designed to be similar to the actual ones and are fixed by bolt to constrain their rotation. The top shape of the rails is also made similar to the actual ones.

The pier type wharf model was used same similarity method with the crane model. Natural period of the prototype pier is about 0.3s~0.7s [Yokota et al, 1998]. The prototype has about 30 piles, but the model has 4 because to simplify, however the equivalent elastic modulus is the same. To exchange the natural period of a pier, we prepared 4 kind of piles and it was interchangeable. **Fig.3** shows models of a container crane and pier type wharf.

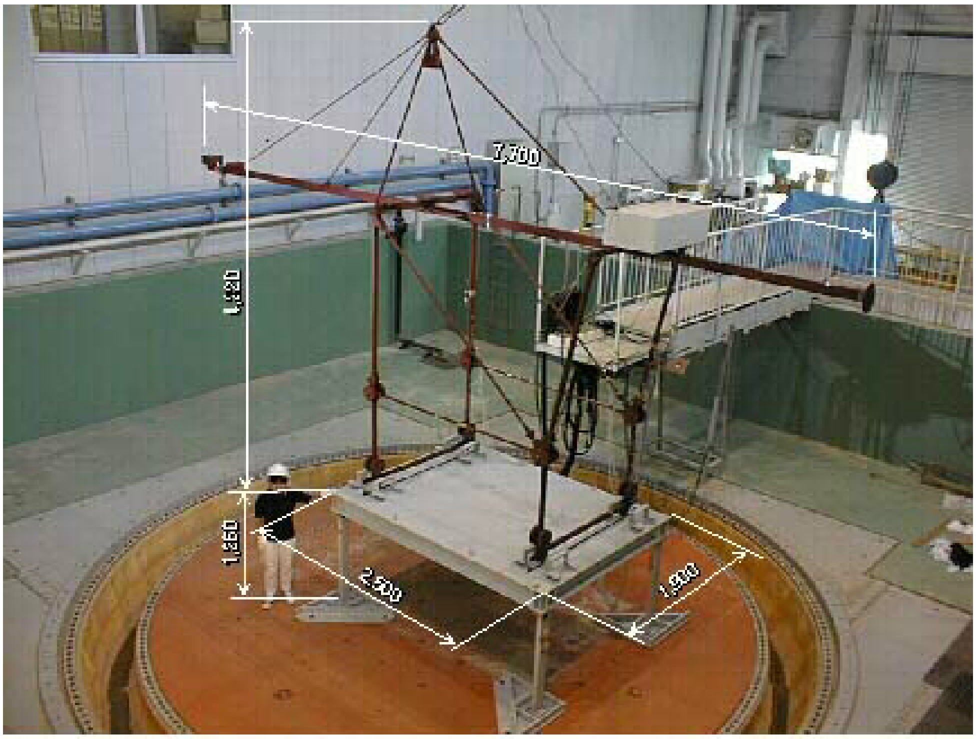


Fig.1 The global over view of the model and shaking table

Table1 Scaling relations between prototype and model

Measured Quantity	Dimensions	Prototype	Model
Length	m	1	1/15
Time	s	1	$1/\sqrt{15}$
Acceleration	m/s^2	1	1
Mass	kg	1	$1/15^3$
Moment of inertia	Kgm	1	$1/15^5$
Elastic modulus	Kg/m^2	1	1
Bending rigidity	Kg/m^2	1	$1/15^5$

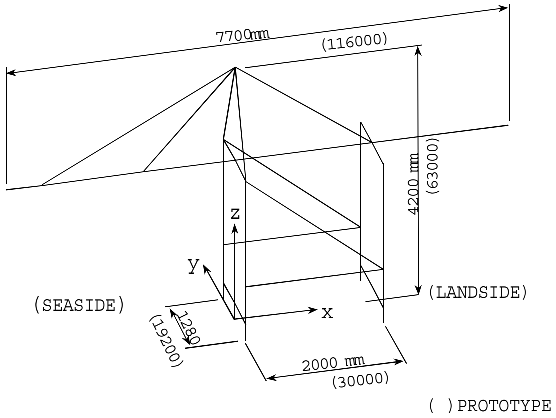


Fig.2 Dimensions of the test model

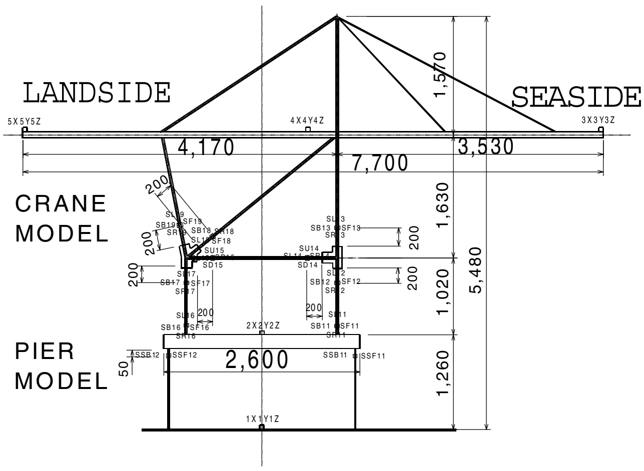


Fig.3 Models of a container crane and pier type wha

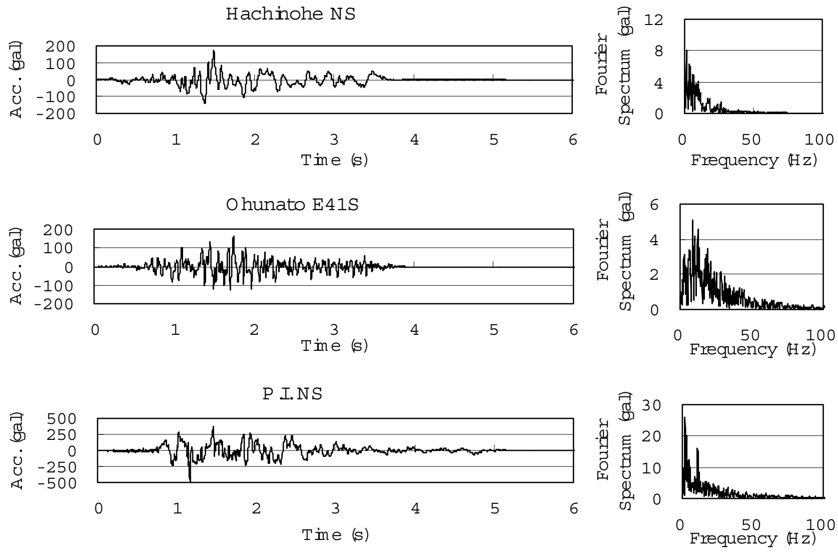


Fig.4 Input waves and their Fourier spectrum

2.2 Input seismic motions:

Input seismic waves were HACHINEHE NS, OHUNATO E41S, and PORTISLAND NS. They are used often at the designing of the port facilities. And sine wave was used, too. **Fig.4** shows input waves and their Fourier spectrum.

The time scale motion is adjusted to be $1/\sqrt{15}$ of its original record to keep the scaling relations. The input acceleration is increased until the crane is derailed.

2.3 Test facility:

3-D dimensional shaking table of Port and Harbor Research Institute, Ministry of Transport located Nagase, Yokosuka, Japan, was used in this test. The shaking table is ϕ6m in dimensions and is driven by a electro-hydraulic system.

In this test, relative displacement between the wheels and the upper part of the pier ware measured by laser displacement meters in vertical direction. Strain gage type accelerometers were used to measure acceleration. Strain gages were applied to measure strain of members. Installation of gages is shown in **Fig.3**.

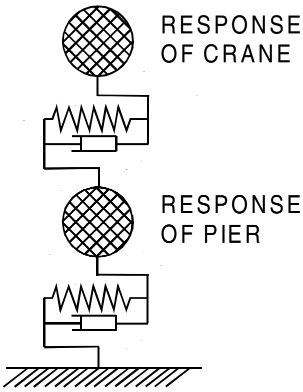


Fig.5 Double decked mass-spring model

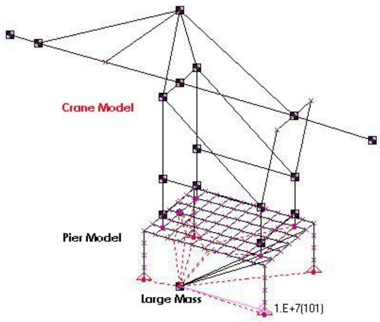


Fig.6 The finite element model

ANALYSIS METODS

3.1 Mass-spring model analysis:

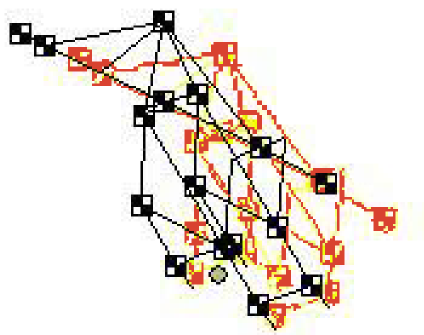
We reduced the actual figures of a container crane and the upper part of the pier as in the mass-spring model. Then, it is computed the motion of each of the mass-spring model during earthquake. The mass-spring model analysis is a simplified simulation method. Because we need easy approach to evaluate and investigate the interaction effect between container crane and pier type wharf during earthquakes. The simplified simulation method is shown in **Fig.5**.

3.2 3-D nonlinear transient response analysis:

The shaking table test was simulated by a nonlinear transient response analysis, employing a multi-purpose finite element analysis code "MSC/NASTRAN for Windows ver.3.0". The finite element model is shown in **Fig.6**. The members of the test model were modeled by beam elements and the additional masses were modeled by concentrated mass elements.

In the eigenvalue analysis, the model is simply supported at the nodes corresponding to the wheels of the model. In the transient response analysis, the boundary condition changes depend on the state of the wheel of the model. When a wheel is on the rail, it is constrained by its flange in the direction along the rail, free in the upward direction and elastically supported in the downward direction. On the other hand, when the wheel is uplifting, it is entirely free, and after the wheel landed on the upper part of the pier out of the rail, it is constrained by friction between the wheel in horizontal direction. To represent these conditions, gap elements were applied at the lower end of the legs, as shown **Fig.6** [San H. Lee, 1992]. The dumping was applied as proportional damping to the stiffness matrix with the coefficient 0.001, determined by the result of free vibration test. The ground motion was applied to the lower end of piles of pier model by large mass method.

MODE1 (13.12Hz)
Fig.7 Eigenmode of Pier



MODE2 (2.198Hz)
Fig.8 Eigenmode of Crane

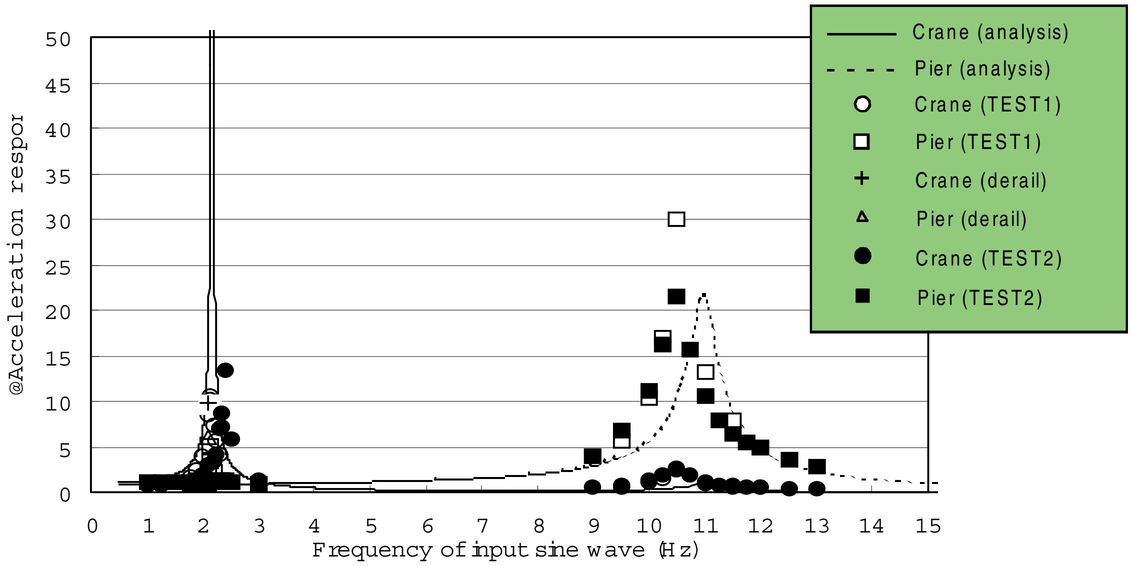


Fig.9 Results of test and analysis using sine waves

RESULT OF THE SHAKING TABLE TEST AND ANALYSISES

4.1 Natural frequency:

Sinusoidal sweep test was carried out with the sweep rate 0.01Hz and the exciting amplitude approximately 20Gal, from which the principal natural frequency of the crane model was identified to be 2.198Hz, the natural frequency of the pier model was identified to be 10.81Hz.

Fig.7-Fig.8 shows the eigenmode of the models by the FEM analysis. The analysis natural frequency of the crane model was 2.195Hz, the analysis natural frequency of the pier model was 13.12Hz, which almost agrees with the test result.

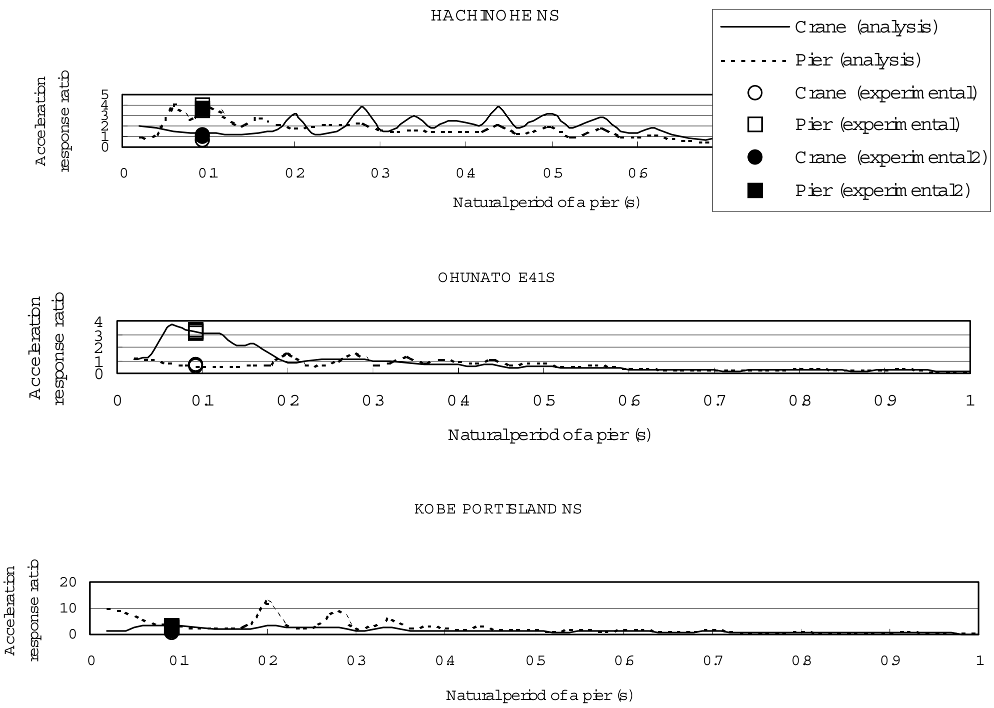


Fig.10 Results of Test and Analysis using seismic waves

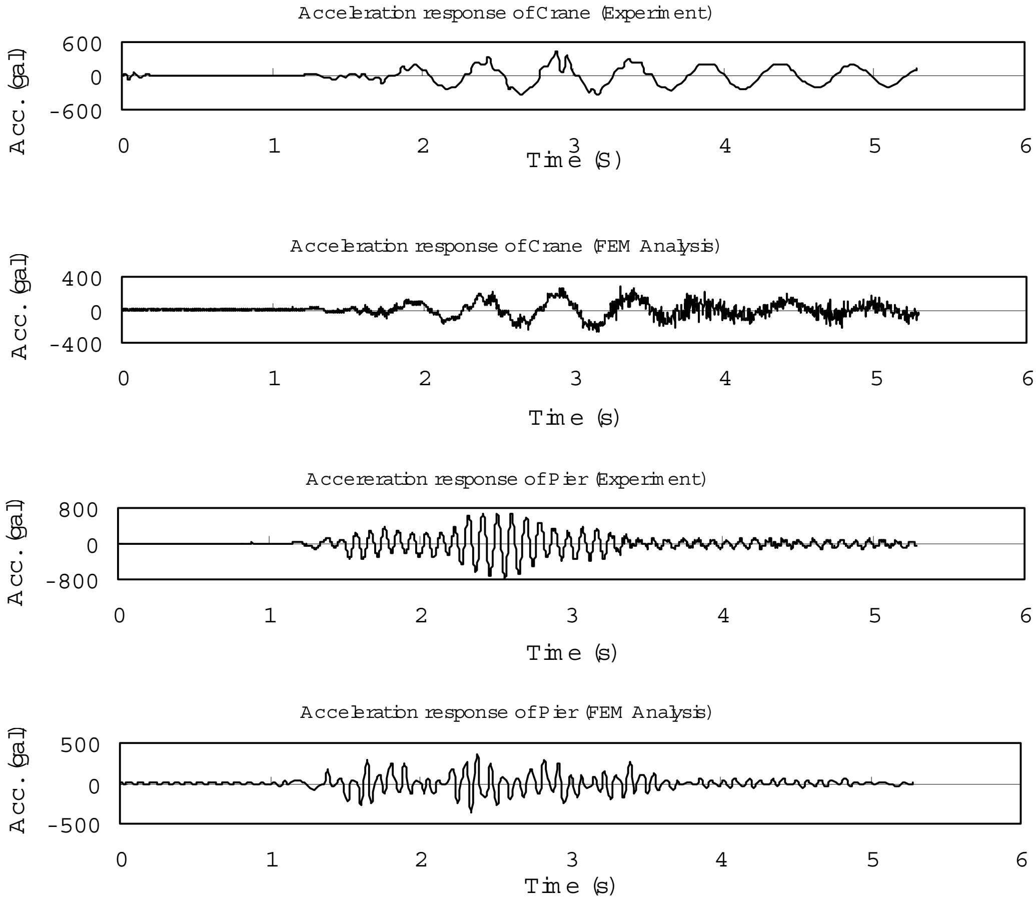


Fig.11 Results of Time history of Test and FEM Analysis

At the crane model, twisting of the structure around the vertical axis constitutes the 1st and 3rd mode. 2nd mode is that of deformation in the direction transverse to rail. Because the motion transverse to the rail is discussed in this paper, dominant responding mode in both the test and analysis is supposed to be 2nd mode.

4.2 Sine wave input:

Fig.9 shows the results of the shaking table test of using sine wave and the double decked mass-spring model analysis. The spring constant and the damping constant were determined by the free vibration test result. The 1st mode of the analysis is about 2.17Hz, and 2nd mode is 10.8Hz. In **Fig.9**, It fixed the leg bottom tip and the upper part of the pier case in TEST2. On the other hand, TEST1 makes free of a crane's leg and the upper part of the pier, it is possible for the uplifting phenomena of crane's legs.

It compares TEST1 and TEST2, the maximum acceleration response ratio of crane of TEST1 is higher than TEST2 but the maximum acceleration response ratio of pier is lower at the resonance point (1st=2.17Hz, 2nd=10.8Hz). It thinks that an input acceleration is eased by the uplifting of the leg and slipping of the wheel about the crane. When the pier with the crane, and moreover the stopper acts, there is an effect which reduces the replying of the pier. In these circumstances, it is considered that the interaction between pier and crane.

4.3 Input seismic motions:

Fig.10 shows the results of the shaking table test of using seismic motions and the double decked mass-spring model analysis. The horizontal axis shows natural frequency of a pier, a vertical axis shows acceleration response ratio. The lines show analysis result, response of crane in solid line and response of pier in dashed line, the points expressing the test results, response of crane in circle and response of pier in square. Those results agree well in the acceleration response ratio.

So, it seems that the double decked mass-spring model analysis can be used for design of the crane and pier type wharf during earthquake. But the double decked-mass spring model analysis is unable to explain derailment phenomena of the crane, so it was done FEM nonlinear transient analysis. Results of the test and FEM analysis in **Fig.11**. The input wave is Kobe Port Island NS component during the 1995 Hyougoken-nambu earthquake. A test and analysis with 40% reduced input acceleration was carried out to investigate the overturning behavior of the model. Test and analysis results of waveform agree well with each other.

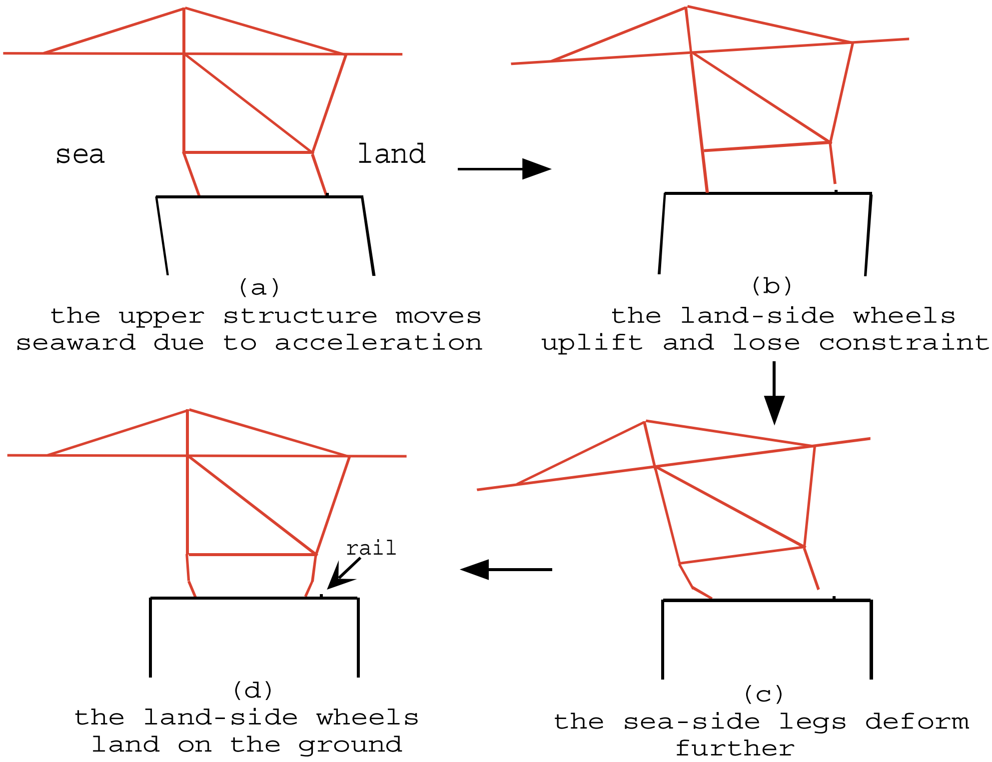


Fig.12 Schematic view of the model behavior

CONCLUSIONS

(1) The shake test and FEM analysis show the behaviors of the crane and a pier during earthquake as follows;

a) When the upper structure of crane and upper part of pier move seaward due to horizontal acceleration.

b) The land-side wheels uplifted and lost their constraint at flange.

c) The axial load in the seaside leg increased and the sea-side legs deformed further.

d) When the horizontal acceleration diminished, the land-side wheels which had uplifted, land on inside from the rails.

This behavior is schematically shown in **Fig.12**.

(2) The double decked mass-spring analysis can be used for design of the container crane without phenomena of uplifting legs and pier type wharf during earthquakes.

(3) The nonlinear transient analysis with Gap element can express the uplifting phenomena of crane's leg during big intensity of earthquake acceleration.

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