Design procedures of seismic-isolated container crane at port

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ABSTRACT :

Most of the container cranes were damaged in Kobe port during the 1995 Hyogoken-Nambu Earthquake. Because the container operation could not be performed, various type of losses were incurred such as economical losses, permanent shift of container ships from Kobe port to other ports, etc. Currently, the seismic design method of a container crane is adopted the 'seismic coefficient method'(pseudo static method). In case of extremely high intensity input seismic motion such as Level 2 input motion, the dynamic behavior of a container crane is expressed in terms of lift off of the legs from the rails and locking motion. The current design method can not treat the behaviors mentioned above. To evaluate and develop the design method for the Level 2 input motion, 1/30 scale model shake tests, simple mass-spring numerical analyses and 3-D dynamic FEM analyses were conducted. From the model shake test results, a threshold acceleration level of the lift off of the legs from the rails showed good agreement with a pseudo static horizontal acceleration of lift off the legs predicted in the design method. Proposed 3-D FEM model of container crane can simulate the dynamic behavior of a crane model during a shake table test even when the legs lifted off from the rails. The simple mass-spring model is also useful numerical method for the case of smaller acceleration level when the legs lift off. In practical point of view, we proposed simplified dynamic response analysis for base-isolated container crane consideration with model tests, 3D-FEM, 2D-FEM, Frame model and simple mass-spring model.

KEYWORDS: Container crane, Seismic Isolation, Soil-Structure Interaction

1. INTRODUCTION

The hyogoken-nambu earthquake which occurred on Jan.17, 1995 destroyed most of major facilities of the Kobe port. Container crane in the port was no exception, and was collapsed or seriously damaged as indicated in Fig.1. It is not an exaggeration that the fact led to a halt in Japanese economic activities seriously.

Fig.1 Destroyed container crane on quay wall at Kobe Port (1995 Hyogoken-nanbu Earthquake)

To avoid such a situation, not only quays but container crane should be designed to resist earthquake ground motion. However, in general, at the design phase of quays, designer often have little specific information about container crane which is needed to make a 3D analytical model of structure, such as weight or shapes of the crane. Still, basic specs for container crane have to be checked at the design stage of a quay to consider dynamic behavior, and to minimize damage of port facility caused by earthquake. Hence, it would be very useful that if we can understand the dynamic characteristic of the container crane with minimum information about the crane.

In this report, we considered the possibility that analytical model simpler than 3D model for a container crane could apply to the seismic design, and the applicability to an actual design was examined.
Container crane with base-isolation system was also examined whether the simple analytical model could be applied to this type of crane or not, since such a system have been developed for practical use recently.

2. SHAKE TABLE TEST FOR CONTAINER CRANE

Scale ratio of the test model was set as 1/15, the prototype crane has about 30m length of rail span and about 10MN weight. Table1 shows the similitude applied for the tests. In making of the model, it was paid attention to match bury centric position and natural period of the model with those of the prototype. Sketch of the model is shown in Fig.2 and the test model was placed on the shake table as shown in Fig.3.
Fig.4 shows the model of base-isolation system which was set to the legs of the crane model, and the internal structure has slide and resilience mechanism. The time history of acceleration on the shake table is as indicated by Fig.5.

Table 1 Scaling relationship between prototype and model[1)]

Measure Quantity	Unit	Prototype	Model
Length	m	1	1/15
Time	s	1	$1/15^{1/2}$
Acceleration	m/s^2	1	1
Mass	kg	1	$1/15^3$
Bending rigidity	Nm^2	1	$1/15^5$

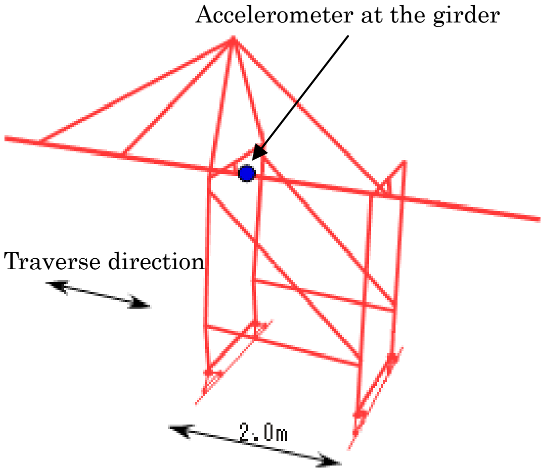


Fig.2 Sketch of the model crane for the experiment

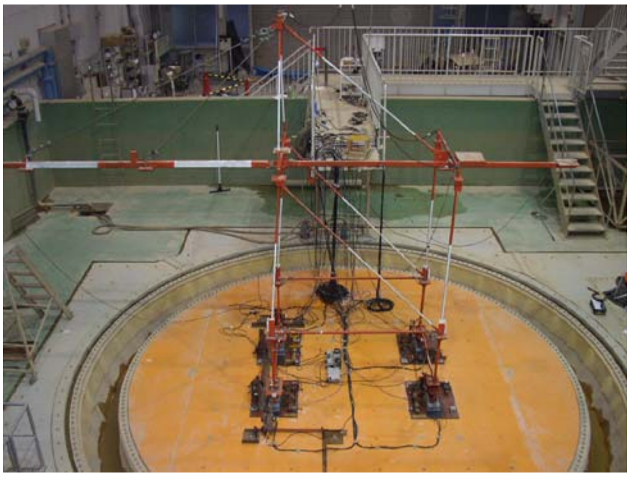


Fig.3 Model setup on the shake table

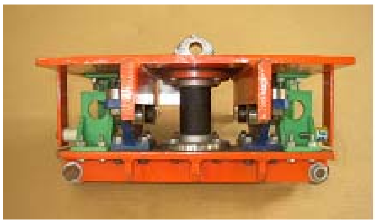


Fig.4 Base-isolation system used for the test

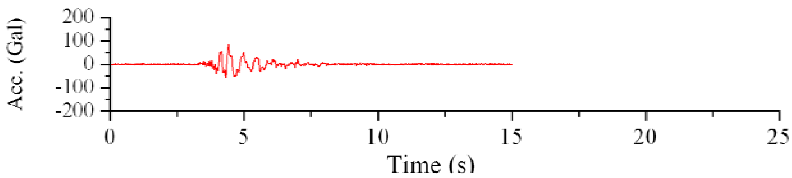


Fig.5 Time history of acceleration on the shake table

Fig.6 is a comparison of time history of acceleration which was obtained at the girder of the model. It is clear that the acceleration was reduced when the base-isolation system was activated. The fact tells the seismic-isolated container crane can reduce the earthquake inertia force acting on itself.

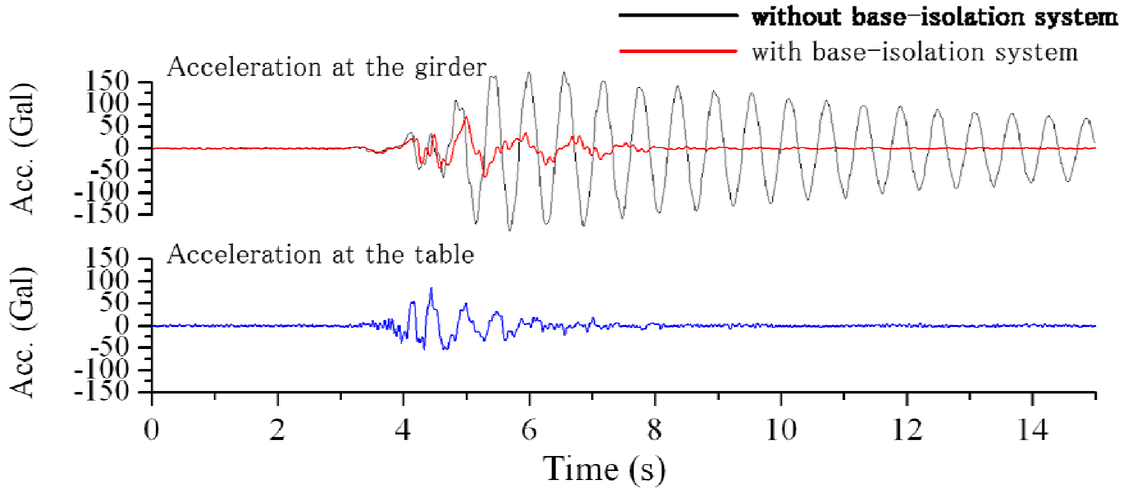


Fig.6 Comparison of time history of acceleration. (Lower indicates the waveform on the shake table.)

3. NUMERICAL ANALYSIS METHOD

3.1 modeling method –without base-isolation system

Various type of numerical analysis were conducted to simulate the experimental results and to examine the possibility that analytical model simpler than 3D model could explain a basic dynamic properties, i.e., the time history of acceleration at the girder. The outline of each model is shown in Fig.7.

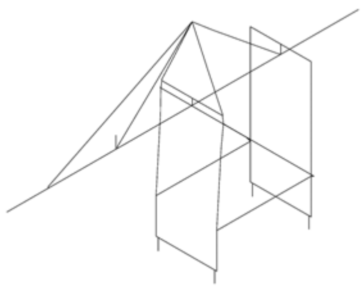
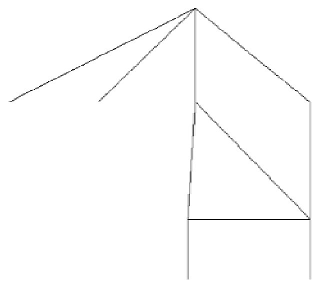
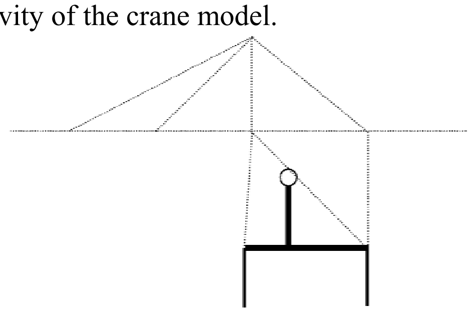
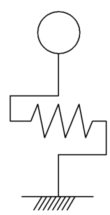
∘ Modeled as 3D frame.  (3D-FEM)	∘Projected on the 2D-plane frame 3D frame model.  (2D-FEM)
∘ Lumped-mass were arranged at the center of gravity of the crane model.  (Frame model)	∘Stiffness of the spring was matched at the natural period of the model. ∘Bumping of the model was given as Rayleigh damping.  (simple lumped-mass model)

Fig.7 Various type of analytical model to simulate dynamic behavior of container crane
(3D-FEM, 2D-FEM, Frame model, and simple lumped-mass model)

a) 3D-FEM model

Parameter of steel at the shake table test was used to make a beam element for the frame model, and the mass which installed for mass adjustment of the test model was given as a nodal concentrated mass.

Dumping of the test model was given as Rayleigh damping which is defined as ;

$$[C] = \alpha[M] + \beta[K] \tag{3.1}$$

Where [C], [M], and [K] are dumping matrix, mass matrix, stiffness matrix, respectively. α and β are coefficient of the matrix. Here, α and β were selected to conform the dumping coefficient of the test model which correspond to its 1^{st} and 2^{nd} natural period of traverse motion. The dumping coefficient *h* was determined by reading from the free vibration part of the time history of acceleration at the girder, and was 1%.

Fig.10 (a) shows the comparison of shake table test and analytical result, and it can be found that the analytical result completely agree with the test result.

b) 2D-FEM model

As we make 2D frame model corresponding to 3D frame model, it is necessary to consider the member property of depth direction, because 2D frame model is the model which is projected on the 2D-plane from 3D frame model. Then, these 3D-effect were devised as follows ; Upper beam supporting girder was replaced to vertical and horizontal spring by using relation between load and displacement, in the case that concentrated load from the girder is acting on the center of a simple beam, as indicated by fig.8. Torsional stiffness of the beam located on the upper traveling unit of the crane was modeled to rotational spring. Dumping of the model was given as Rayleigh damping, as well as in the case of 3D frame model. (Value of *h* is 1%)

The result of analysis is shown in fig.10 (b). As the diagram indicates, It turns out that each result of experiment and analysis are in good agreement till 8 seconds on the graph when principal motion of the input motion seems to be finished. Also, it can be seen that phase lag have occurred at the free vibration part. This is attributed to the fact that ,while the natural period of 2D frame model was 0.583 second, that of 3D was 0.589 sec.

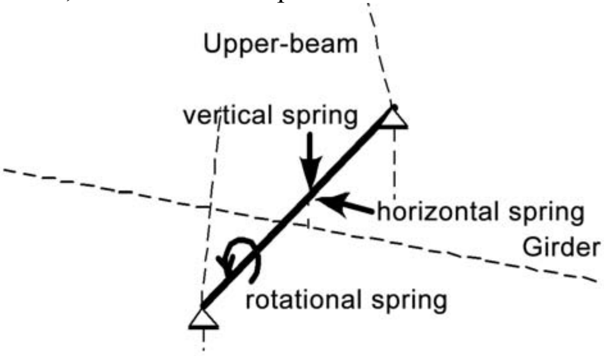


Fig.8 The method of replacing for 2D frame model

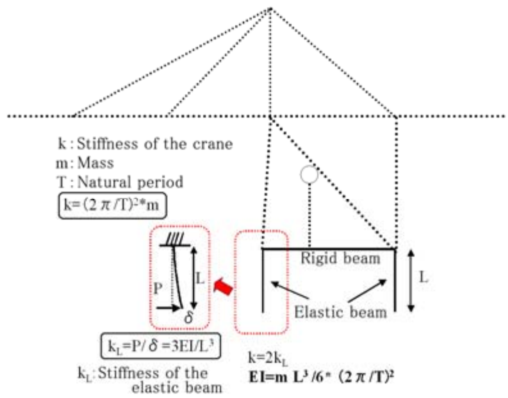


Fig.9 Elastic coefficient of the Frame model

c) Frame model

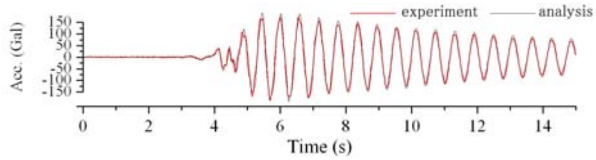
To make frame model, lumped mass were arranged at the center of gravity of the crane model, seaside-leg and landside-leg of the model crane were modeled as a massless elastic beam, horizontal girder and members connecting horizontal girder with lumped mass were modeled as a massless rigid beam. The stiffness of elastic beam was set to match the natural period, 0.589sec, of the test model, as the cantilever beam fixed at horizontal girder shown in Fig.9.(EI=5.91kN・m^2)

The result is shown in Fig.10(c). There is little difference between the waveform of experiment and of analysis, despite the time history of the analysis indicates the result at lumped mass.

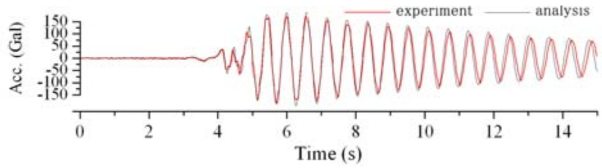
d) Simple lumped-mass model

This model is composed only of lumped mass and spring which is supporting the mass. Stiffness of the spring was matched at the natural period of the model crane. Dumping of the model was given as Rayleigh damping, in

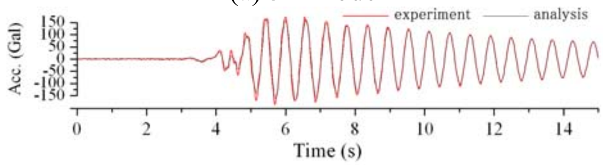
the same way as mentioned above.
Waveforms of the acceleration are compared in Fig.10 (d), and it is clear that experimental result and its analytical simulation are corresponding well.



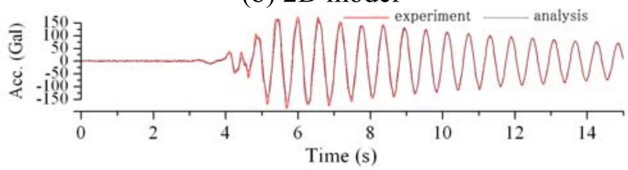
(a) 3D model



(b) 2D model



(c) Frame-model



(d) lumped-mass model

Fig.10 Comparison between the analytical and experimental result of the time history at the girder (Acceleration).

3.2 modeling method – base-isolation system is operated

As identified above, it was observed that dynamic response characteristics of a container crane could be simulated well even if the lumped-mass model was used, when the base-isolation system was not operated.
In this section, another case was considered, the isolation system was operated. Outlines of the analytical model are shown in the following. Concepts of dumping in each model were emphatically described below, because the basic idea of the analysis model is same as noted in section 3.1.

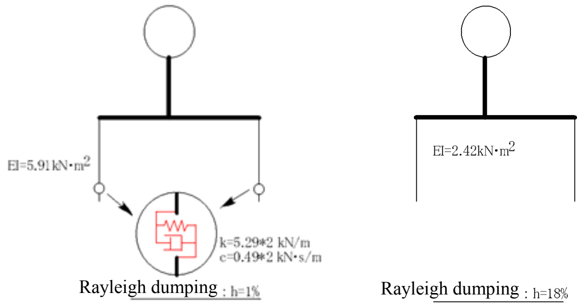
a) 3D FEM model
Seismic isolator was modeled by spring element and dumper element. Stiffness of the spring element was set to correspond to the natural period of the crane, with the operating isolation system. Dumping factor of the dumper element was set by reading from the time history. And Rayleigh dumping was given as dumping of the main frame, which was corresponding to h=1%.
The result of analysis agrees well with experiment, as indicated by fig.13 (a).

b) 2D FEM model
Each value of spring element and dumper element that used in 3D frame model was doubled so that one element exerts the effect corresponding to two legs of the crane. Analytical result is shown in fig.13 (b), and the tendency is similar to the case with 3D frame model.

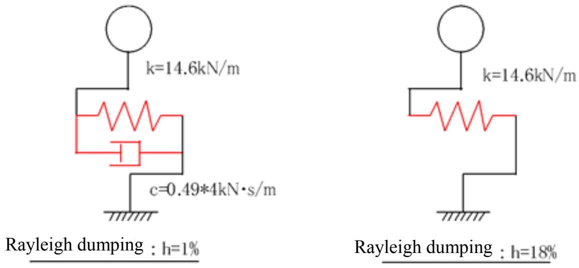
c) Frame model
Two types of analytical model for rigid frame model were examined; One model has spring element and dumping element similar to 2D FEM model(Model c-1), the other is the model that stiffness of elastic beam and Rayleigh dumping were set(Model c-2).The stiffness of elastic beam in Model c-2 was decided from the natural period of the crane.(EI=2.42kN･m^2) Dumping of whole structure is corresponding to h=18%, which was obtained by reading from the free vibration part of the time history of acceleration at the girder.
Comparing Fig.13 (c1) and Fig.13 (c2), it can be seen that degree of agreement of experiment result and analysis result are comparable. This fact indicates the possibility that we can analyze the response characteristics of container crane with base isolated, even if the simple rigid frame model as shown in Fig.11(b) was used for dynamic analysis.

d) Lumped-mass model
Here also, two types of analysis for lumped-mass model were conducted in a similar way to c), and outline of these model are shown in Fig.12. In Model d-1, the effect of dumper elements was expressed as Rayleigh dumping, and spring stiffness was calculated by using the natural period of the test model.(With the operating

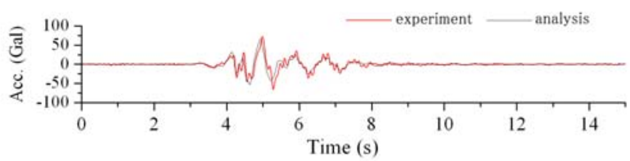
isolation system.)
As shown in Fig.13 (d1), maximum acceleration of analysis result is lower than that of experiment, and phase lag between the waveform is observed. In this method, it seems that the dumping in the analytical model is too heavy. On the other hand, for Model d-2, it turns out that analytical result is corresponding to experimental one well, as indicated in Fig.13 (d2).



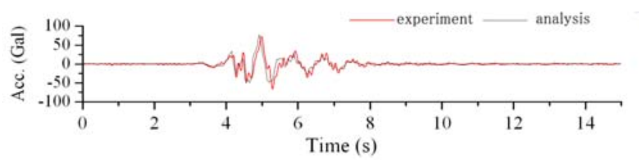
(a) Model C-1 (b) Model C-2
Fig.11 Modeling method for rigid model



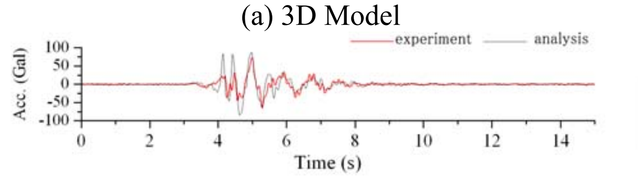
(a) Model D-1 (b) Model D-2
Fig.12 Modeling method for lumped-mass model



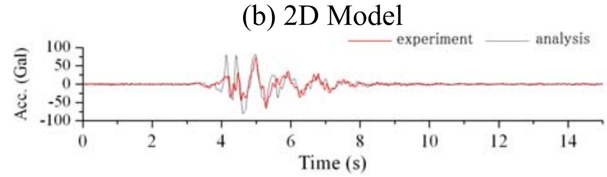
(a) 3D Model



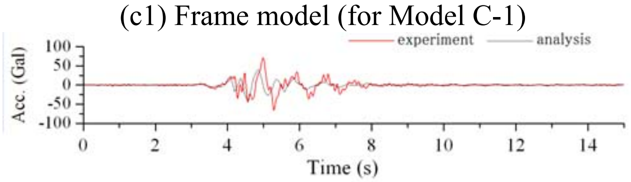
(b) 2D Model



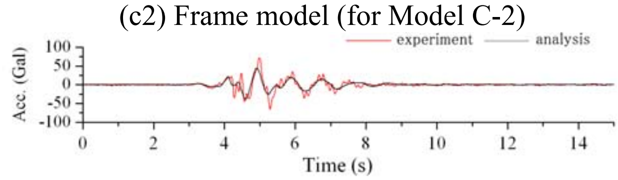
(c1) Frame model (for Model C-1)



(c2) Frame model (for Model C-2)



(d1) Lumped-mass model (for Model D-1)



(c2) Lumped-mass model (for Model D-2)

Fig.13 Comparison between the analytical and experimental result of the time history at the girder (Acceleration).

4. APPLICATION FOR THE ACTUAL DESIGN

Having seen above. It has been shown that basic dynamic behavior of the container crane can be estimated enough by using a simple lumped mass model. In the following, the authors describe that how to apply this simplified model to an actual seismic design for a container crane. According to the typical fracture mode of the container crane, one side legs of the container crane lifted up from its rail by inertia force acting on the crane, then full weight load of the crane acted on the other side legs, as a result, buckling failure occurred on the legs of the crane[2)]. From the fact, it is important to consider the threshold horizontal acceleration from which the legs of the crane start to lift off from its rails is at the design phase of facility. (This acceleration is defined as ,"lift acceleration" , in following)
Fig.14 shows the relation between maximum acceleration of input motion and the acceleration at the girder, when

various seismic motion were input on the shake table, in which the same crane model as indicated in chapter 2 was used. It seems that the lift-up occurs when the acceleration exceeds certain value. In this figure, theoretical lift acceleration which is obtained by solving equation of equilibrium is also shown, drawing upon fig.15.

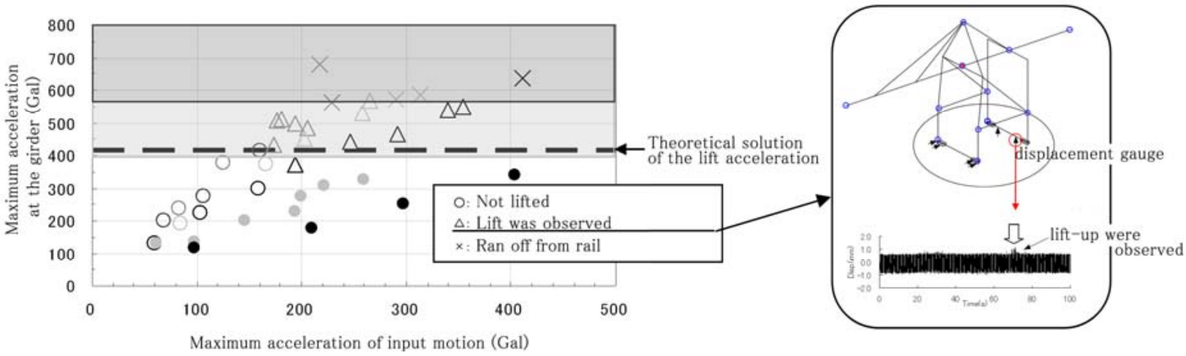
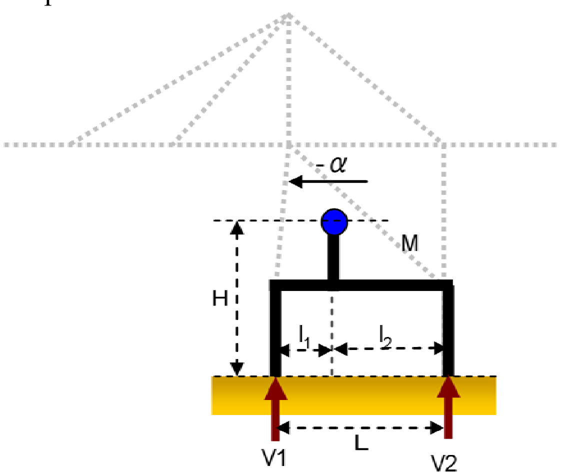


Fig.14 The relation between maximum acceleration of input motion and the acceleration at the girder

From this result, threshold of lift acceleration obtained by experiment and that obtained by static analysis (indicated in fig.15) are corresponding well. Moreover, because the acceleration at bury center of the crane can be computed by using lumped-mass model, we can figure out the lift acceleration with comparative ease by using this simple method.



Moment equation at the seaside-leg :

$$L \cdot (V_2) + H \cdot m \cdot (-\alpha) - l_1 \cdot m \cdot g = 0$$

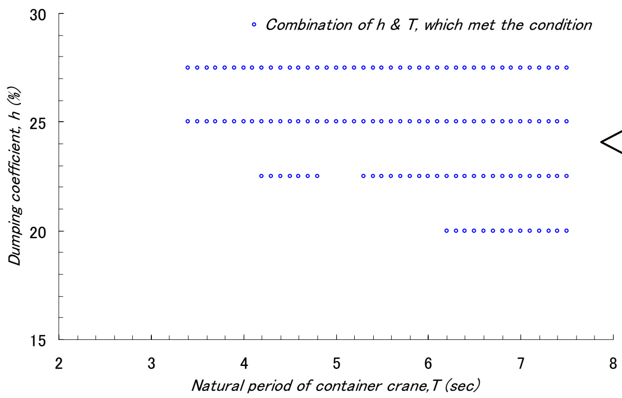
V_2=0, when the landside-leg starts to lift.
Lift acceleration can be described as ;

$$(-\alpha) = \left(\frac{l_1}{H}\right) g$$

α: acceleration at the girder m: mass
g: gravity acceleration V: axial force

Fig.15 Theoretical solution of the lift acceleration (static analysis)

By the way, needless to say, it has effect that a crane with isolation system can reduce inertia force acting on it, on the other hand, it sometimes happens that displacement of those crane responds too large. At the design phase of quays, threshold of response displacement of container crane should be considered as design condition, as there is a possibility that deformation value of isolation system (e.g. ; deformation value of laminated rubber used as isolation system) exceeds the limit value. However, we have to take note that the response displacement obtained by using simple lumped-mass model indicates the displacement of the center of gravity of the container crane. So it has to be more investigated that the relation between the deformation value of isolation system and the response displacement of the center of gravity of the container crane, or those relation for other types of isolation system . At any rate, we can determine the minimum design condition for the container crane on the quay wall by using the analytical result of lumped-mass model that meet the conditions, both maximum acceleration and displacement of the center of gravity of the crane.



<Analysis conditon>

- Simple lumped-mass model was used for the analysis[3]. And combination of h &T, which met the both condition (following) are plotted in above figure.
- Threshold of maximum acceleration and displacement of the container crane are 450Gal and 100cm each.
- Dumping coefficient *h* is given as its total system.

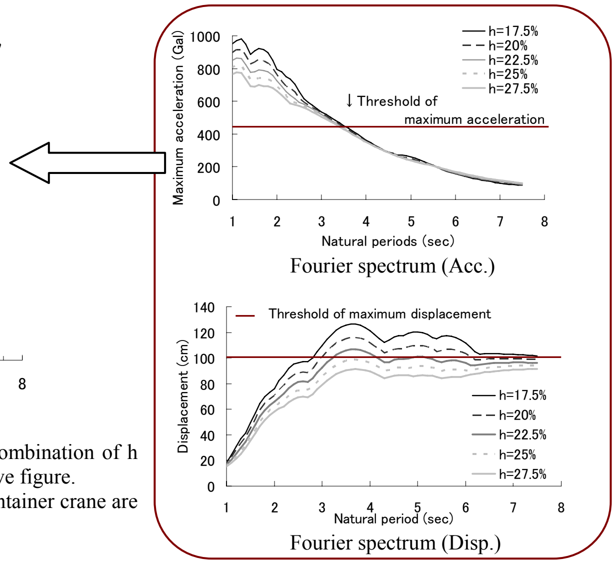


Fig.16 Basic required performance for the container crane on the quays at design phase (As an example)

5.CONCLUSIONS

In this report, we considered the possibility that analytical model simpler than 3D-FEM model for a container crane could apply to the seismic design, and the applicability to an actual design was examined. According to the results, the following findings were obtained.

1) The acceleration at the girder of the container crane was reduced when the base-isolation system was activated. The fact tells the seismic-isolated container crane can reduce the earthquake inertia force acting on itself.
2) Basic dynamic response characteristics of a container crane could be simulated well even if the lumped-mass model was used, whether container crane has isolation system or not.
3) The "lift acceleration" of the container crane gave close agreement with the acceleration which solved by static analysis that axial force of the landside-leg of the crane supposed as 0. This shows that "lift acceleration" can be simulated enough by using simple lumped-mass model, because acceleration at the center of gravity of the crane can compute by using those simple method.
4) At the design phase of the quays, it is necessary for seismic design of the container crane that both acceleration and displacement of the center of gravity of the crane have to be set as design condition, since the deformation value of isolation system also should be considered. Meanwhile, between the response displacement of the center of gravity of the crane and deformation value of isolation system have to be more investigated.

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