ま え が き

本報告はＵＪＮＲ耐風耐震構造専門部会第８回合同部会に提出した資料の一部をまとめたものである．この合同部会はアメリカ合衆国ワシントン特別区で開催されたもので大型実験研究部長木下武雄が日本側部会出席者の一員として出張，論文発表を行ない合同部会の討論，決議に参加した．

国立防災科学技術センターはこの専門部会に発足時から委員を送り，強震観測，大型振動実験，耐風耐震の研究現況等の題目で論文発表を毎年の合同部会で行なっている．また，この合同部会は隔年毎にアメリカ合衆国ワシントン特別区で行なわれるため，過去の第２回，第４回，第６回にもこの第８回と同様，国立防災科学技術センターから研究担当の部長または室長１名を日本側部会員として派遣し，ＵＪＮＲ耐風耐震構造専門部会の活動の一端をになっている．

本報告書は，提出論文と日本語の概要を記載し，ＵＪＮＲにおける国立防災科学技術センターの活動を明らかにし，また，今後当センターの活動が国際的にも理解されるようにとの目的で刊行した．

大型実験研究部長
木　下　武　雄

防災科学技術研究資料　第２３号　1976年8月

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REVIEW OF RESEARCH FOR DISASTER PREVENTION No.23 August 1976

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Review of Research for Disaster Prevention No.23 August 1976

Large-scale Testing Programs Related to Wind and Seismic Effects Currently Underway in Japan

Seiichi Inaba

Earthquake Engineering Laboratory

National Research Center for Disaster Prevention

Science and Technology Agency

Task Committee of Japan Panel

on Large-scale Testing Programs

The 8th Joint Meeting

U.S.-Japan Panel on Wind and Seismic Effects

UJNR

Washington, D.C. May 18-22,1976

Review of Research for Disaster Prevention No.23 August 1976

Large-scale Testing Programs Related to Wind and Seismic Effects Currently Underway in Japan

Seiichi Inaba

Scope

This list has been prepared for the discussion dealing with cooperative research problems in the area of large-scale testing of structures on the 8th Joint Meeting of U.S.-Japan Panel on Wind and Seismic Effects. The Japan Panel selected the following four members to work for the task committee on large-scale testing programs.

Seiichi Inaba, National Research Center for Disaster Prevention

Makoto Watabe, Building Research Institute

Kenkichi Sawada, Public Works Research Institute

Nobuyuki Narita, Public Works Research Institute

In accordance with the exchange of letters between Dr. C. Culver of the National Bureau of Standards of U.S. Panel and Mr. S. Inaba of Japan Panel, this list has been drafted to inform the U.S.-Japan Panel of work going on in the area, and the list includes the large-scale testing programs currently underway in Japan, the organization, the name of individual in charge, and a brief description of the objectives, status and time schedule.

The following three experts have cooperated with our task committee for the preparation of the list.

Toshio Iwasaki, Public Works Research Institute
Hajime Tsuchida, Port and Harbour Research Institute

Keiichi Komada, Honshu-Shikoku Bridge Authority

Yukiyoshi Ibe, Resources and Energy Agency

The author, serving as co-chairman of the task committee, is responsible for the entire work for the preparation of the list, contact with the U.S. Panel, and proposals to the Japan Panel.

Program: Dynamic Tests of Structures by Use of the Two-dimensional Shaking Table

Organization: National Research Center for Disaster Prevention

Names in Charge: Seiichi Inaba, Nobuyuki Ogawa; Earthquake Engineering Laboratory.

Description of the Objectives:

It is planned to study the effects of the vertical earthquake shaking on structures using the two-dimensional shaking table, which is going to be built in the National Research Center for Disaster Prevention. The table will have the size of 6 m X 6 m, and the maximum test weight of 60 tons will be allowable for the simultaneous vibration of vertical and one horizontal directions up to the maximum displacements of ±100 mm for horizontal and ±50 mm for vertical vibration. Maximum velocities of 60 cm/sec for horizontal and 40 cm/sec for vertical, and maximum accelerations of 1.2 G for horizontal and 0.8 G for vertical direction will be worked out, and the frequency range between D.C. and 30 Hz will be covered.

Dynamic test programs are planned on the large-scale models of embankment and other soil structures, building structures, plant structures foundation structures and so forth.

Status:

Soil exploration of the foundation site was done in 1974. Feasibility study of the two-dimensional shaking table has been carried out. A small-scale model simulator of table size of 1 m X 1 m was constructed in March, 1976.

Time Schedule:

Designs of the shaking table, foundation and laboratory building is carried out in 1976, and the construction of foundation will start in 1977. Dynamic test will start in 1980 after the completion of the construction.

Program: Dynamic Tests of Composite Breakwater

Organization: Port and Harbour Research Institute, Ministry of Transport

Names of individuals in charge: Setsuo Noda, Tatsuo Uwabe, Hajime Tsuchida, and Satôshi Hayashi

Description of the objectives:

Recently several composite breakwaters of large height are under planning in Japan. The composite breakwater consists of a rock-fill or sand-fill mound and concrete caissons resting on the mound. The largest breakwater of this type in Japan has been constructed in Ofunato Bay to protect coastal area along the bay from hazard by tsunami; the breakwater is 40 meters in height. The breakwater against tsunami must have sufficient seismic stability since it is certain that the breakwater will be shaken due to earthquake ground motions preceding tsunami arrival.

The Port and Harbour Research Institute (PHRI) is planning to examine the seismic stability of the composite breakwater by model tests. At present the tests are expected to be performed on a shaking table in PHRI, which is an electro-dynamic random shaking table having frequency range from 0.2 to 100Hz. Size of a container on the table is 5 meters in length, in direction of table motions, 1.5 meter in width, and 1.5 meter in depth. A wave absorving channel can be connected with a flexible joint to the container to eliminate disturbance by waves generated and reflected by an end wall.

Through the tests stability of rock-fill mound, dynamic water pressure to the mound and the caissons, and relative displacement between the mound and the caissons will be studied.

PHRI has been observing earthquake ground motions at the site of the tsunami breakwater in Ofunato Bay and its earthquake response. The records obtained in the observation will be analysed as a part of the study.

Status:

PHRI has some experiences on dynamic tests of such a composite breakwater; in the tests, however, a small model was used and the model was tested in air.

The earthquake ground motion records at the site of the breakwater and records of its earthquake responses were once briefly analysed and reported in the following report:

Hajime Tsuchida, Tatsuo Uwabe, Eiichi Kurata, and Satoshi Hayashi: Observation and Analysis of Earthquake Response of Fill Type Breakwater, Proceedings of the Japan Earthquake Engineering Symposium 1973 in commemoration of the 50th anniversary of the Kwanto earthquake, August and September 1973, pp. 375-364.

Time schedule:

The tests are expected in late 1976 or in 1977 Japanese fiscal year (from April to March).

1. Program: Experimental Investigation into the Seismic Behavior of Full-size Reinforced Concrete Structures Utilizing the Large Scale Testing Facilities.

2. Organization: Building Research Institute, Ministry of Construction

3. Names of individuals in charge: M. Watabe
M. Hirosawa
S. Nakata

4. Description of the objectives:

Up to date many experimental studies were made on the columns, beams and shear walls. However there are many fields still unexplored; stress distribution among each member of structures at the variable plastic stage, yielding mechanism as a structure and ductility of each member at a yielding mechanism of structure. For example the aseismic tests (static and dynamic) of full size structure with slabs, shear walls and foundations need be carried out. These test results would make clear the difference between the behavior of structure and unit member especially the anchorage of main bars or ground effects on walls and so on. Hitherto the studies on the structural damage due to earthquake were based only on member tests in laboratory, and the behavior of structures as a whole had to be based on many engineering assumptions. Such assumptions may lead the study to some mistakes. Full size structural testing should be made in order to avoid such mistakes.

As a first stage of testing project, we propose 3 story buildings with shear walls. The kind of shear walls include normal type, precast wall and slit wall. By doing this test, such problems as actual behavior of shear walls, effects of foundation, soil condition and mechanism at structural yielding will be explored. All the types of buildings as following cases should be included in the project, i.e. structures without shear wall with short columns or long columns, long span structures and many types of ground conditions.

Large Size Loading Facility in Building Research Institute is for static and dynamic full size structural tests by hydraulic servo actuators, which is now under construction and is to be used in 1979. All the testing systems, loading, vibration and measurement are directly controlled by a computer system in this facility. The total cost of this project is expected to be 12 billion yen(40 million dollars).

5. Status: M. Watabe et al, "A Proposal to the Joint Research Program on the Aseismic Properties of R.C. Structure by the Full Size Specimens." 7th Joint Meeting U.S.-Japan Panel on Wind Seismic Effects, UJNR, Tokyo, May 20-23, 1975.

6. Exchange of Research Personnel:

1976
- E. Pfrang (N.B.S.)
- A. Sozen (Univ. of Illinois)
- R. Hanson (Univ. of Michigan)
- H. Umemura (Univ. of Tokyo)
- H. Aoyama (Univ. of Tokyo)
- M. Watabe (B.R.I.)

1977
- J. Penzien (E.E.R.C.)
- R. Clough (E.E.R.C.)
- P. Jennings (T.I.C.)
- T. Okada (Univ. of Tokyo)
- M. Murakami (Chiba Univ.)
- Y. Yamazaki (B.R.I.)

1978
- M. Duke (U.C.L.A.)
- E. Popov (E.E.R.C.)
- M. Hirosawa (B.R.I.)
- A. Shibata (Tohoku Univ.)
- Y. Matsushima (B.R.I.)

1979
- R. Bresler (E.E.R.C.)
- J. Penzien (E.E.R.C.)
- R. Clough (E.E.R.C.)
- Y. Ohsawa (E.R.I., Univ. of Tokyo)
- S. Nakata (B.R.I.)

Program: Dynamic Test of Structures for Nuclear Power Plants
Organization: Center for Nuclear Safety Engineering Research
Names in charge: Resources and Energy Agency, Ministry of International Trade and Industry

Description:

Construction of a shaking table for testing the nuclear power plant structures is planned to prove the safety of nuclear power plant during and after the future destructive earthquakes. Part of the funds has been admitted from the government since 1975.

The structures for dynamic tests include containers, pressure vessels, elements of reactors and piping of main -coolant system for both PWR and BWR nuclear power plants.

The shaking table under planning will have the dimension of 15x15 m, maximum test weight of 1000 tons, maximum stroke of ±200 mm for horizontal direction and ±100 mm for vertical direction. The table could be driven to the simultaneous vibration of one horizontal and vertical directions up to the accelerations of 2g for horizontal and 1g for vertical and the velocity of 70 cm/sec for horizontal and 35 cm/sec for vertical direction.

The total cost of construction including the shaking table, foundation and the laboratory building is expected to be 24.8 billion yen (83 million dollars) and the construction cost of a test structure for a year will be about 2 billion yen (7 million dollars).

The model scale of test structures will be 1/4 for container of 800 MWe PWR and 1/2 for that of 1100 MWe BWR power plants.

Status:

Construction of the table and the research work will be carried out by the Center for Nuclear Safety Engineering Research which is established under the control of the Resources and Energy Agency by the end of February, 1976. The center is a joint government-private foundation supported from the government and the electric power companies, constructors and manufacturers.

Time Schedule:

It will take 5 years to build the shaking table and the laboratory and other testing facility. The shaking tests will begin in 1981.

Program:

Dynamic Experiments on Earthquake Resistance of Civil Engineering Structures

Organizaton: Public Works Research Institute, Ministry of Construction

Name in Charge: Ground Vibration Section and Earthquake Engineering Section, Public Works Research Institute, Ministry of Construction

Description:

Construction of shaking table is planned to prove the earthquake resistance of engineering structures such as suspension bridges, prefabricated submerged tunnels, underground piplines, embankments, etc.

There are two kinds of shaking-table facilities under planning. One will have the dimension of 6 meter x 8 meter, maximum test weight of 130 tons, maximum stroke of ±75 mm, maximum velocity of 60 cm/sec, maximum acceleration of 0.7g in the horizontal direction. The other will have 4 shaking tables, and each table will have the dimension of 2 meter x 3 meter, maximum test weight of 30 tons, and other specifications are almost the same as the above large scale shaking table. These two kinds of shaking tables will use 4 actuators in common.

The total cost of construction including the shaking tables, foundation and laboratory building is expected to be 1.2 billion yen (4 million dollars).

Status:

Dynamic tests of suspension bridges, using 4 electro-magnetic type exciters had been conducted about ten years ago. Dynamic tests of submerged tunnels and underground pipes, using the large scale shaking table belong to the Earthquake Engineering Laboratory, National Research Center for Disaster Prevention, Science and Technology Agency, had been conducted several years ago. An experiment on dynamic behavior of sandy grounds during earthquakes now carried out, using the shaking table which have the dimenssion of 1.5 meter x 2 meter, maximum test weight of 5 tons in the horizontal direction.

Time Schedule:

It will start in 1977 to build the shaking tables and the laboratory and other testing facilities at Tukuba Science City, and it will take 2 years to complete a part of those facilities. Dynamic tests will be expected to start in 1979.

Program: Dynamic Test of the Suspension Bridge Foundation Model

Organization: Honshu-Shikoku Bridge Authority

Name in Charge: Keiichi Komada, Chief of the Third Design Division

Summary:

In order to prove the safety of the bridge foundations at the time of earthquake, dynamic model test by the large scale shaking table is planned to carry out in 1976. It is aimed to clarify the interaction between the foundation and ground. Thus the response of the foundation and ground will be measured for various depth of the foundation model.

An outline of the test and analysis is as follows:

1) Model:

Foundation Model: 60x80x100 cm (Weight: 1 t)

Ground Model: 400x900x150 cm

2) Exciting Waves:

Sinusoidal Wave, Random Wave and Earthquake Wave

3) Measurements:

Acceleration Response of the Foundation and Ground

4) Analysis:

Experimental Analysis of Resonance Curves, Vibration Modes and Others

Theoretical Analysis of Response by the Finite Element Method

Status:

Honshu-Shikoku Bridge Authority has been excuting the dynamic test to develope the earthquake proof design of the various type of the foundations, since 1971. Those details are shown in Table 1.

Table 1 Details of Experiments

Year	Type of Foundation	Ground Material	Measurement
1971	Rigid Foundation and Multi-Column Foundation	Rubber	Acceleration and Displacement
1972	Rigid Foundation and Multi-Column Foundation	Grouting Material	Acceleration and Displacement
1973	Rigid Foundation and Rigid Foundation with Piles	Grouting Material	Acceleration and Displacement
1974	Rigid Foundation	Sand	Acceleration, Displacement, Soil Pressure and Pore Pressure

Program: Dynamic Test of Embankment

Organization: Public Works Research Institute

Names in charge:

Kenkichi Sawada, Yasuyuki Koga: Soil Dynamics Section

Description of the Objectives:

The object of our research is to explain the dynamic behavior of the embankment, using the large-scale shaking table established at National Research Center for Disaster Prevention.

The height of the test embankment is 1.5 m and the depth of the ground base is 1.5 m. The total length of the model is 12 m perpendicularly to the embankment axis and the width is 2 m. In addition to this basic model, the embankments protected with the steel sheet piles and the horizontal sand berm are tested. The model embankment is constructed in a water tight steel box on the shaking table and the model is perfectly or partially submerged in water depending on the test program.

The test of embankment on a saturated ground soil is the fundamental and important case. Data of the increase of pore water pressure and acceleration of the model are obtained. Analysis using slice method to evaluate the stability of the embankment is applied to explain the slope failure due to the dynamic vibration considering the effects of pore water pressure increase in embankment and ground soil. Analysis is also done to the liquefaction problem under anisotropic stress condition.

Status:

Results of this test program have been published on the Tecnical Report of Public Works Research Institute and presentet on the Annual Conference of Japan Society of Soil Mechanics and Foundation Engineering. A paper on the settlement of saturated sands due to vibration was presented on the UJNR U.S.-Japan Joint Panel on Wind and Seismic Effects in 1975.

Time Schedule:

We have been engaged in the research program for 5 years since 1970. Our future program for several years aims the behavior of vertical vibration of the embankment, soil-foundation interaction, and soil structures constructed with other materials such as steel sheet piles, concrete slabs, retaining walls and so forth.

Program

Aerodynamic Test for Long-span Bridges and High-rise Towers

Organization

Public Works Research Institute, Ministry of Construction

Names of individuals in charge

N. NARITA, Chief, Structure Section and K. YOKOYAMA Res. Eng., St. Sec.

Description

Two large wind tunnels are now being constructed. The main feature of these wind tunnels is as follows ;

(1) Wind tunnel for flutter testing of bridge and tower structures

Dimension of test section : 2.5 x 4.0 m (10 m long)

Maximum wind speed : 25.0 m (without coarse grid)

21.0 m (with coarse grid)

(2) Wind tunnel for aerodynamic testing of bridge and tower structures under turbulent flow

Dimension of test section : 6.0 x 3.0 m (30 m long)

Maximum wind speed : 15.0 m/s

(3) Location of the facilities

Tsukuba Science City in Ibaraki Prefecture about 60 kilometers northeast of Tokyo

(4) Completion

The construction work will be completed in May 1977.

The following wind tunnel tests are scheduled to be carried out ;

(1) Measurement of aerostatic and aerodynamic forces acting on bridge or tower structures.

(2) Measurement of critical flutter speed of the structures.

(3) Measurement of aerodynamic response of the structures under gusty and turbulent wind.

(Manuscript received 1 June 1976)

防災科学技術研究資料　第23号　1976年8月

日本における耐風耐震に関する大規模実験計画

国立防災科学技術センター大型実験研究部耐震実験室

稲　葉　誠　一

この資料は耐風耐震構造専門部会の第8回合同部会において構造物の耐風耐震に関する大規模実験計画の作業部会の討論資料として作成したものである．本報告では日本において現在行なわれている大規模実験計画，各計画の研究機関，研究担当者，研究目的，経過と将来計画に関して述べてある．個々の計画名及び研究機関は以下に述べるようなものである．

1. 計 画 名：二次元振動台の使用による構造物振動実験
   研究機関：国立防災科学技術センター
2. 計 画 名：混成防波堤の振動実験
   研究機関：港湾技術研究所
3. 計 画 名：大型実験施設を利用する実大鉄筋コンクリート構造物の振動挙動の実験的研究
   研究機関：建築研究所
4. 計 画 名：原子力発電所施設の構造物の振動実験
   研究機関：原子力工学試験センター
5. 計 画 名：土木構造物の耐震性に関する振動実験
   研究機関：土木研究所
6. 計 画 名：吊橋基礎模型の振動実験
   研究機関：本州四国連絡橋公団
7. 計 画 名：盛土の振動実験
   研究機関：土木研究所
8. 計 画 名：長大支間の橋梁，超高塔状構造物の空気動力学的実験
   研究機関：土木研究所

Review of Research for Disaster Prevention No.23 August 1976

Research on Earthquake Effects on Electric Power Equipment

-- Dynamic Test of a Circuit Breaker for Transformer Substation --

Seiichi Inaba

Shigeo Kinoshita

Earthquake Engineering Laboratory

National Research Center for Disaster Prevention

Science and Technology Agency

The 8th Joint Meeting

U.S.-Japan Panel on Wind and Seismic Effects

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Washington,D.C. May 18-22, 1976

Review of Research for Disaster Prevention No.23 August 1976

Research on Earthquake Effects on Electric Power Equipment

--- Dynamic Test of a Circuit Breaker for Transformer Substation ---

Seiichi Inaba

Shigeo Kinoshita

Summary

It is needed to secure the electric power supply systems during and after the future disastrous earthquakes. Many of the earthquake damages to the electric power industry have resulted from the structural failure of porcelain insulator which are commonly used for the electric transmission equipment.

A dynamic test of a circuit breaker of 72/84 killovolts for the transformer substation was carried out using the large-scale shaking table of the National Research Center for Disaster Prevention in 1975. The test was done under the sponsorship of the Meidensha, a Japanese Manufacturer of electric power equipment. The purpose of test was to find the dynamic characteristics of the prototype structures shielded with the porcelain insulator. Sinusoidal waves of resonant frequency and earthquake simulated waves were applied to the test structure. It was found that the failure of the porcelain insulator governs the seismic resistibility of the circuit breaker and the maximum allowable acceleration at the top of the structure is 8.0 g.

1. The Objectives

The purpose of the dynamic test was to investigate the earthquake effects of a circuit breaker. The three-wave resonance method was applied to the test. The three-wave resonance method is a dynamic test procedure to induce three successive waves with the same frequency as that of the resonant vibration of the test structure and to evaluate the earthquake resistance defined at the first excursion failure.

2. N-wave Resonance Dynamic Test

Since there is no general input waves for vibration test, the selection of appropriate input waves is required for each test. Determinate function waves such as sinusoidal waves or earthquake simulated waves are used for the test and resonant vibration of sinusoidal waves is also used as an earthquake loading. N-wave resonance method is to give N cycles of sinusoidal waves at resonant frequency of the structure and to observe the transient state of vibration. Main purpose of the dynamic test is to evaluate the structural failure defined as the first excursion failure, where any of deflection, strain, or stress of the structure reaches the fracture limit due to the dynamic force. While fatigue failure is for the stationary state of structure, first excursion failure is for the transient state, in which N-wave resonance method is appropriate as the dynamic test prcedure for evaluating the first excursion failure.

2.1 N-wave Resonance Vibration of Spring-mass system with Damping

We consider here a viscously damped spring-mass system excited by harmonic waves at resonant frequency. The equation of the motion can be written as

$$\frac{d^2y}{dt^2} + 2h_n w_n \frac{dy}{dt} + w_n^2 y = -\frac{d^2u}{dt^2} \qquad \text{--- 1}$$

$$u(t) = \sin w_n t \quad ; \; 0 < t < NT_n = 2\pi N / w_n \qquad \text{--- 2}$$

where w_n is the natural frequency in radians per second, h_n is the damping factor, $y(t)$ is the relative displacement and $u(t)$ is the foundation displacement. And the solution is expressed as,

$$\frac{d^2y}{d\,t^2} = \frac{w_n^2}{2h_n}\cos w_n t - \frac{w_n^2 D_n}{2}\sin\left(w_n(1-h_n^2)^{\frac{1}{2}} t + \theta_n\right)\exp(-h_n w_n t) \quad \text{---3}$$

where D_n, and θ_n are written as

$$D_n = 1/(h_n(1-h_n^2)^{\frac{1}{2}}) \;,\quad \theta = -\tan^{-1}\left((1-h_n^2)^{\frac{1}{2}}/h_n\right) \quad \text{---4}$$

Maximum responce in terms of acceleration amplification during N-wave resonance vibration is

$$A_N(h_n) = \frac{1}{w_n^2}\left|\frac{d^2y}{d\,t^2}+\frac{d^2u}{d\,t^2}\right|_{max} \quad \text{---5}$$

For the stationary state of resonant vibration,

$$A(h_n) = \left(\frac{1+4h_n^2}{4h_n^2}\right)^{\frac{1}{2}} \quad \text{---6}$$

Result of computed $A_N(h_n)$ is shown in Fig. 1.

2.2 Analysis of Porcelain Insulator

A circuit breaker is constructed with a frame and a porcelain insulator which is divided to breaker insulator and supporting insulator. An analytical model of continuous system as shown in Fig. 2 is considered and the equation of vibration excited by the harmonic motion is written as,

$$\frac{\partial^2 y}{\partial t^2} + k^2 b^2 \frac{\partial^4 y}{\partial x^4} = -\frac{\partial^2 u}{\partial t^2} \;,\qquad u(t) = \sin w_n t \quad \text{---7}$$

where u(t) is the motion at x=0, y(x,t) is the relative motion of the system, k is the innertia radius of the section, and $b^2 = E/\rho$. E is Young's modulus and ρ is the density. Frequency equation is given as,

$$1 + \cos m \cosh m = 0 \quad \text{---8}$$

and the natural circular frequency is written in terms of solution m_j as,

$$w_j = kb(m_j^2/\ell^2) \;,\; j=1,2,3,\cdots \quad \text{--- 9}$$

And normal function at $m=m_j$ is

$$v_j(x) = \cos\frac{m_j}{\ell}x - \cosh\frac{m_j}{\ell}x - \frac{\cos m_j + \cosh m_j}{\sin m_j + \sinh m_j}\left(\sin\frac{m_j}{\ell}x - \sinh\frac{m_j}{\ell}x\right) \quad \text{---10}$$

and the solution of equation 7 is

$$y(x,t) = \sum_{j=1} v_j(x)\, q_j(t) \quad \text{---11}$$

where $q_j(t)$ is the generalized coordinates. The equation of n-th mode is equivalent to the motion of the one-degree-of-freedom spring-mass system with viscous damping written as,

$$\ddot{q}_n + 2h_n w_n \dot{q}_n + w_n^2 q_n = -\beta_n \ddot{u} \qquad \text{---12}$$

where β_n is the participation factor and it is written as,

$$\beta_n = \int_0^{\ell} v_n(x)\,dx \Big/ \int_0^{\ell} v_n^2(x)\,dx \qquad \text{---13}$$

Therefore the amplification factor due to the N-wave resonance excitation is given as,

$$v_n(x)\beta_n A_N(h_n) \qquad (\,0 \leq x \leq \ell\,) \qquad \text{---14}$$

and Table 1 shows the participation factor β_j (j=1,2,3,$\cdots$), and the normal function v_j(j=1,2,3,$\cdots$) is given in Fig. 3.

Considering these results of theoretical analysis, the bending moment of the system for the 1st mode of vibration is written as,

$$M(x,t) = EI\frac{\partial^2 y(x,t)}{\partial x^2} = EI\frac{d^2 v_1(x)}{dx^2} q_1 = \frac{EIm_1^2}{\ell^2} v_1(\ell - x)\, q_1 \qquad \text{--- 15}$$

v_1 is the maximum at $x=\ell$, and the $M(x,t)$ is the maximum at $x=0$, then

$$M_{max} = M(0,t) = \frac{E\,I\,m_1^2}{\ell^2} v_1(\ell)\, q_1 \qquad \text{--- 16}$$

Therefore M_{max} is proportional to the relative displacement at the top of the porcelain insulator, and stress and strain will be given as,

$$\sigma(x,t) = M(x,t)/\,Z(x)\ , \quad \epsilon(x,t) = \sigma(x,t)/\,E \qquad \text{--- 17}$$

$Z(x)$ is the section modulus.

3. Dynamic Test of the Circuit Breaker

Vibration tests on the shaking table were carried out to observe the dynamic response of the structure, and also possibility of leakage of air-pressure and defects of functions of equipment were tested before and after the table excitation. No functional deficiency was found even after the excessive loading up to the acceleration of 0.3 g.

3.1 Test Structure

Test structure of the circuit breaker of 72/84 killovolts and 1200 ampere is constructed with a frame and a porcelain insulator shown in Fig.4. The porcelain insulator is composed of the upper breaker insulator and the lower supporting insulator. The insulator of each phase has the dimension of 2.2 m of height and 900 kg of weight and material is porcelain. The lowest end of the supporting insulator has a larger diameter to have much strength and to be cemented and bolted to the frame structure. Therefore the maximum stress of the insulator is measured at the second fold from the lowest end, where the critical strain related to the first excursion failure can be observed.

The result of the static test show that the critical strain for failure is 780×10^{-6} ($=\epsilon_0$), and the static allowable stress is 5.85 kg/mm^2 since the Young's modulus of porcelain is 7500 kg/mm^2. Insulators of each phase are called A,B, and C phase insulater respectively. For the test on the shaking table test, the supporting frame was bolted to a steel panel and the panel was fixed to the shaking table with bolts.

3.2. Instrumentation and Measurement

Two directions of horizontal excitation were chosen to the test as given in Fig. 4 and are named short axis test and long axis test. Accelerations and strains of porcelain insulator were measured using accelerographs and strain gages as shown in Fig. 4, in which points of G_1- G_8 are for accelerographs and points of S_1- S_{17} are for strain gages.

3.3 Vibration

Harmonic excitations of sinusoidal waves in the frequency range between 0 Herz and 10 Herz which cover the frequency range of earthquake waves were induced to find the frequency characteristics of the system including the support frame and to decide the test frequency of three-wave vibration. Before the harmonic ocsilation, the table was driven by an instataneous step displacement of 0.5 mm to induce the free vibration of each phase insulators and to decide the approximate natural frequency and damping factor. Then the sinusoidal wave at the acceleration level of 0.03 g was applied to the structure until the stationary response was observed at each frequency , which was changed between 1 Herz and 10 Herz by the pitch of 0.2 Herz near the resonance. These harmonic excitations were done to the two directions mentioned before.

The Meidensha, the manufacturer of the circuit breaker, was mainly interested in the three-wave resonance vibration test. Resonant frequency was defined as the frequency where the maximum amplification was measured in terms of acceleration at the top of the porcelain insulator compared with the table acceleration.

Three successive sinusoidal waves at resonance frequency of f_n, and also at the frequencies of $f_n \pm 0.2$ Herz were applied to the test at the acceleration level of 0.3 g. Two directions of excitation were used and the states of equipment for breaker-on stage and for breaker-off stage were tested.

Normal white noise input waves at the level of 0.05 g for 30 seconds and the simulated earthquake waves of El Centro 1940 N-S direction were also induced for the dynamic test.

4. Test Result and Discussion

The supporting frame and the porcelain insulators of the circuit breaker are functionally coupled but they are considered to be structurally independent. As to the earthquake effects on the system, the porcelain insulators are more important than the frame.

4.1. Natural Frequency and Damping Factor

Damping factor and natural frequency of the insulator can be given from the analysis written in Section 2. From results of dynamic tests the natural frequency of 1st mode is approximately 9 Herz for long axis direction and 6.8 Herz for short axis direction, and the damping factor is approximately 0.02. Natural frequencies of higher modes are given as

$$F_j = (m_j/m_1)^2 F_1 \qquad \text{---18}$$

And the natural frequency of second mode F_2 is 56 Herz, therefore the vibration of 1st mode is important referring to the frequency range of the earthquake vibration.

4.2. Acceleration of the Porcelain Insulator

Maximum acceleration of the insulator due to the N-wave resonance vibration of 1st mode is

$$G_N(x,h_1,U)= v_1(x)\cdot\beta_1\cdot A_N(h_1)\cdot U \qquad \text{---19}$$

where U is the amplitude of input acceleration and $A_N(h_1)$ is obtained from Fig. 1 and $v_1(x)$ is calculated from equation 10. Fig. 5 shows the maximum acceleration at N=3, h_1= 0.02, $x=\ell$, and the test results of G_2 and G_8. Even though the input frequency of the table is not the same as that of the frame, and the initial condition of excitation is not exactly the same as that of the analysis, results shown on Fig. 5 can be used as the criteria for the maximum acceleration at the top of the insulator.

4.3. First Excursion Failure

We consider the first excursion failure in terms of strain and the strains were measured during dynamic tests. Maximum strains are observed at the second porcelain fold from the bottom and proportional to the relative motion at the top of the insulator.

The linear relationship between the maximum strains and the measured acceleration at the top was found from the dynamic tests as shown in Fig.6 and Fig. 7. The equation of this relationship is written as

$$S \text{ (maximum strain)} = 100\times 10^{-6}\times G \text{ (maximum acceleration)} \quad \text{---20}$$

Equation 20 is confirmed for the maximum strain of 570×10^{-6} from the test and the maximum fracture strain decided from the static test is 780×10^{-6}. Assuming that the equation 20 is valid for the strain of 780×10^{-6}, the first excursion failure will be caused at the acceleration of 8.0 g at the top of the insulator.

4.4. Earthquake Resistance of the Porcelain Insulator

We consider that the earthquake resistance of the porcelain insulator governs the whole system of the circuit breaker. The equation of first excursion failure decided from the N-wave resonance vibration of 1st mode is written as

$$G_N(\ell,h_1,U)=v_1(\ell)\cdot\beta_1\cdot A_N(h_1)\cdot U = G_0 \quad \text{---21}$$

where G_0 is assumed to be 8.0 g from the test results. Since then the safety factor at the three-wave resonance vibration for the input acceleration of U will be written as,

$$P_3 (U) = G_0 /(v_1(\ell)\cdot \beta_1 \cdot A_3 (h_1)\cdot U) \quad \text{---22}$$

Fig. 8 and Fig. 9 show the relationships between the safety factor $P_3(U)$ and the input acceleration of U. Fig. 10 shows the relationship between the safety factor $P_N(U)$ and the number of waves of resonant frequency of 1st mode at the input acceleration U=0.3 g assuming h_1 equarls 0.02.

4.5. Seismic Effects on the Circuit Breaker

The main purpose of the dynamic test was to evaluate the effects of the earthquake vibration on the circuit breaker including porcelain insulator and supporting frame. The safety factor of the breaker obtained from the test is given as the following, where the maximum strain of the support insulator at second fold is $\epsilon_3(U)$,

$$Q_3 (U) = \epsilon / \epsilon_3 (U) \qquad \text{---23}$$

The test data of Q_3 (U) assuming $U = G_1$ are plotted on the Fig. 8 and Fig. 9. It was affirmed that the safety factor $P_3(U)$ can be used as a more conservative criterion than the test data $Q_3(U)$ of the circuit breaker and we can evaluate the seismic resistance of the circuit breaker on the bases of this criteria given from three-wave resonance vibration test.

4.6. Earthquake Wave Test

Earthquake simulating waves of El Centro 1940 N-S direction were applied to the test structure. The maximum strains are approximately 40% of the three-wave resonance vibration test for long axis direction, and 70 % of that for short axis direction. The three-wave resonance test seemed to give conservative criteria for practical design comparing with the earthquake simulating wave test.

5. Conclusions

Conclusions of the dynamic test of the circuit breaker are summarized as the following,

1) The allowable acceleration at the top of the porcelain insulator related to the first excursion failure is 8.0 g.
2) The maximum allowable input acceleration to the circuit breaker is greater than 0.5 g, where the safety factor equals unity.
3) The number of successive sinusoidal waves at resonance is more than 9 on assumption that the safety factor equals unity and the input acceleration is 0.3 g.
4) Acceleration or strain responce due to simulated earthquake is less

than the 70 % of maximum acceleration or strain observed for the three-wave resonance vibration test at the input acceleration of 0.3 g.

6. Acknowledgments

Considerable assistance was received from the other members of the Earthquake Engineering Laboratory, National Research Center for Disaster Prevention, particularly Mr. Nobuyuki Ogawa and Mr. Chikahiro Minowa both in arranging the input waves, and Mr. Haruo Iida and Mr. Takeshi Kubota both in operating the large-scale shaking table for the dynamic test. Additional assistance was received from Dr. Takeo Kinoshita, Head of the Large-scale Testing Division, National Research Center for Disaster Prevention. This project forms a research program sponsored by the Meidensha.

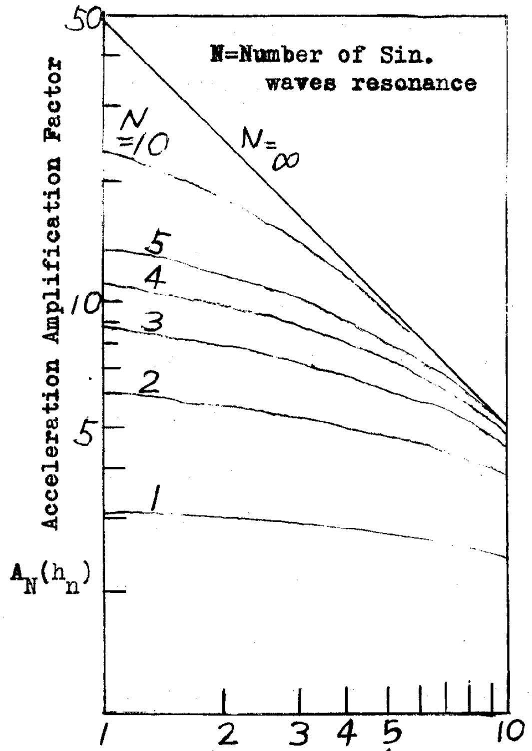


Fig. 1

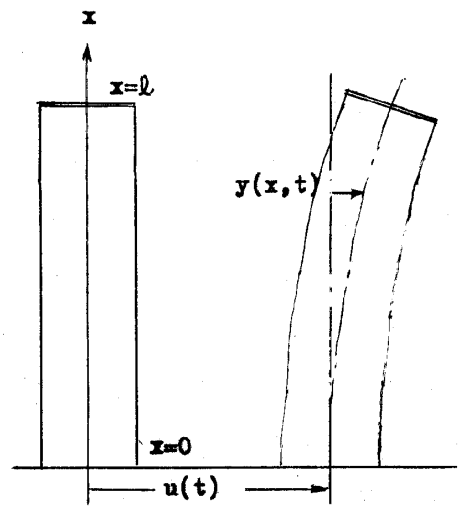


Fig 2 Model of Insulator

Table 1
Participation Factor β_j

j	m_j	β_j
1	1.8751	-0.87
2	4.6941	-0.43
3	7.8548	-0.25
4	10.9955	-0.18
5	14.1372	-0.14

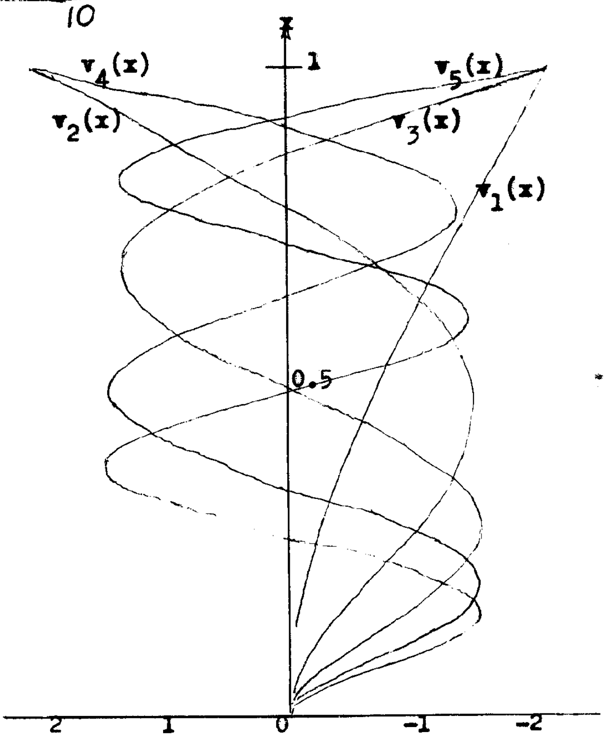
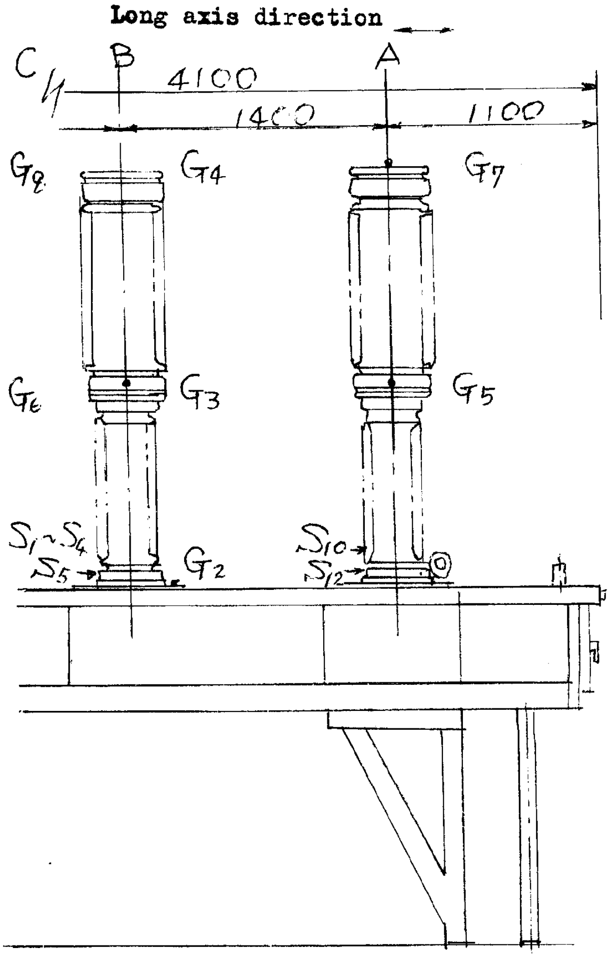


Fig. 3 Normal Function $V_j(X)$



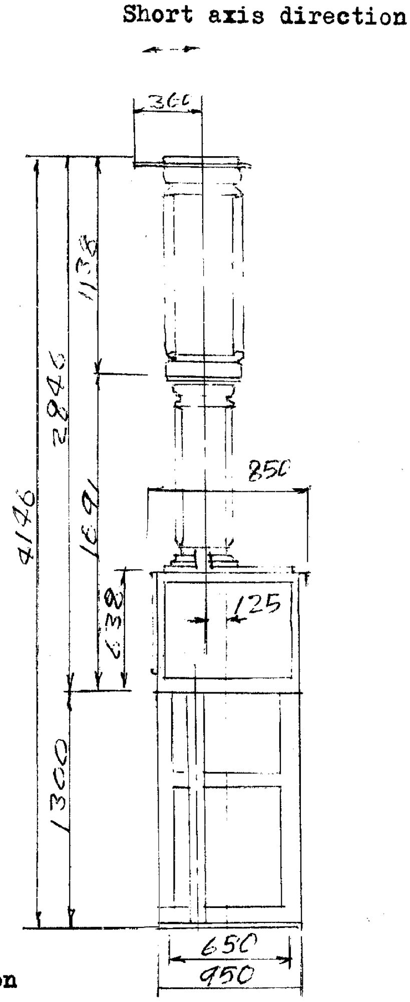


Fig. 4 Circuit Breaker and Instrumentation

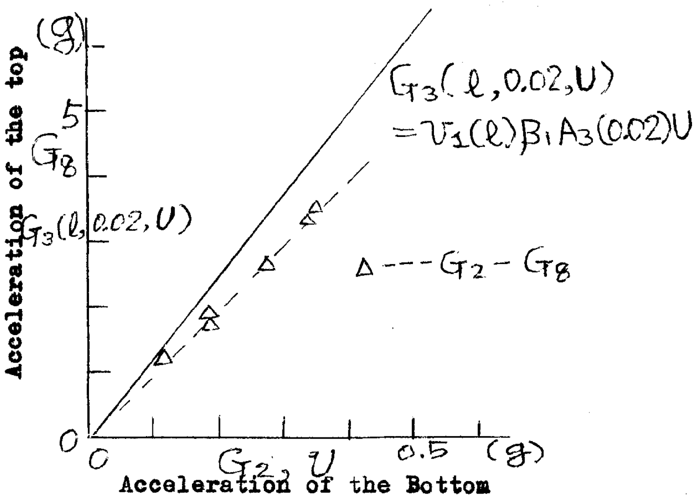


Fig. 5

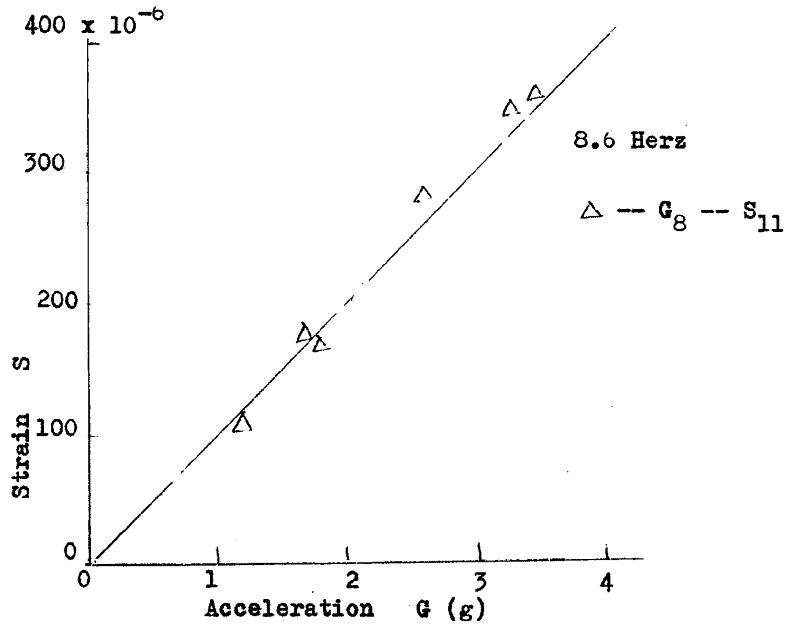


Fig. 6 Long Axis Direction

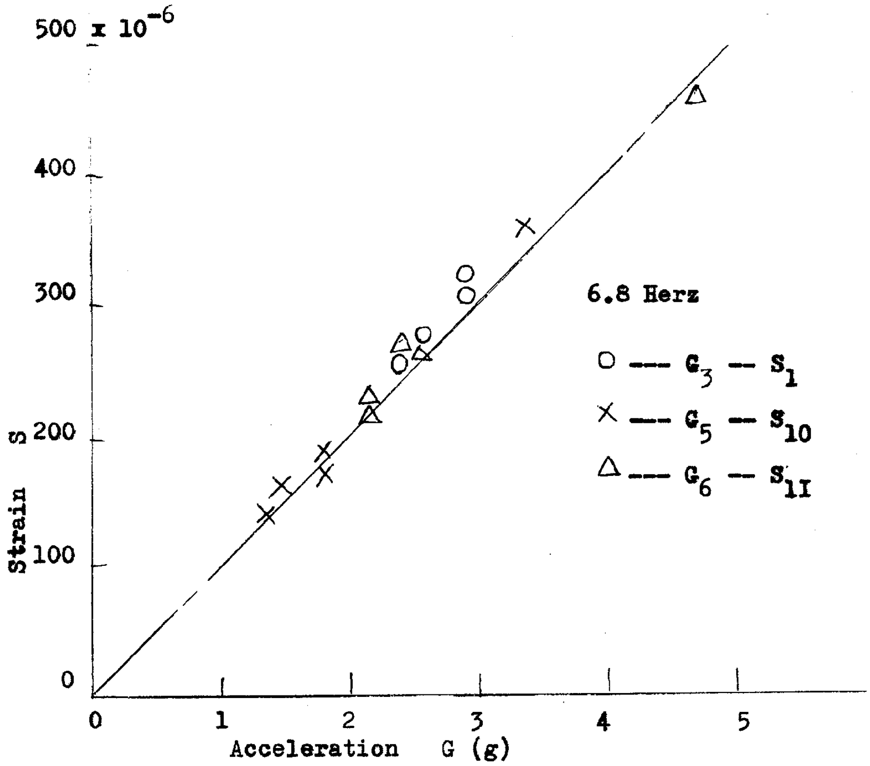


Fig. 7 Short Axis Direction

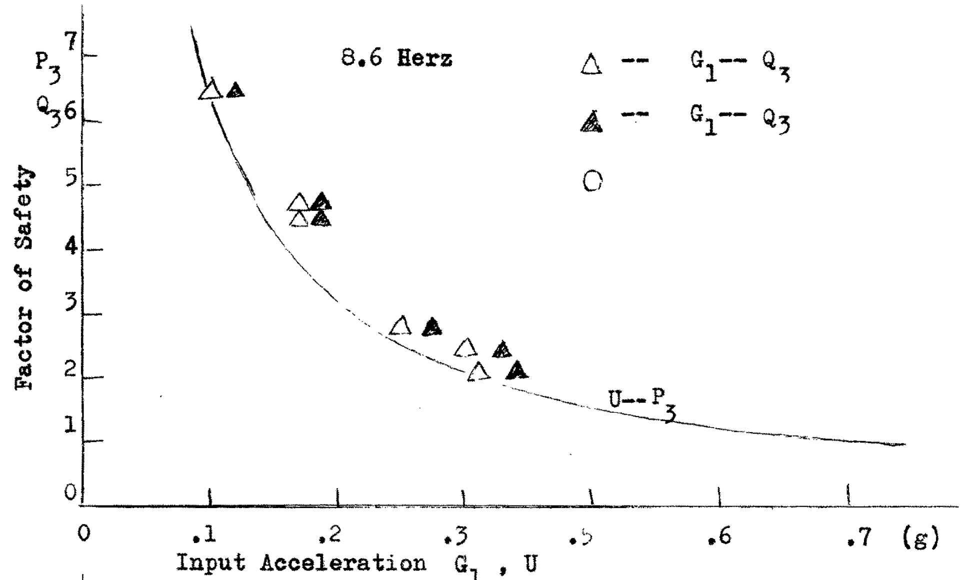


Fig. 8 Long Axis Direction

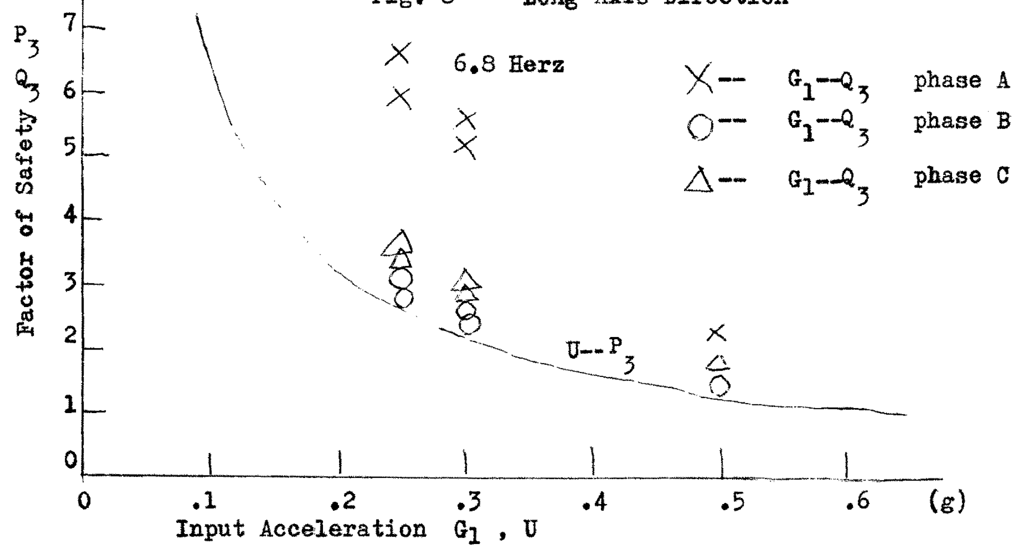


Fig. 9 Short Axis Direction

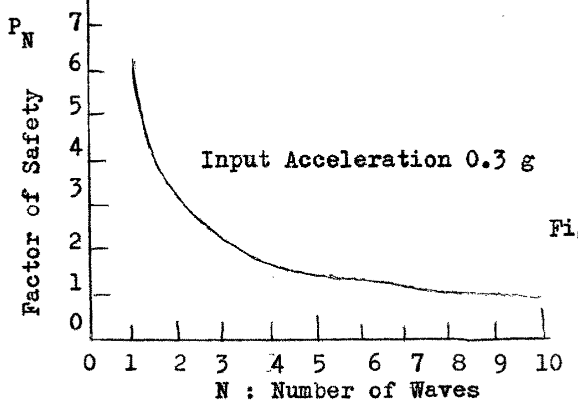


Fig. 10 Factor of Safety and Number of Waves of Resonance

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電力用機器の耐震性に関する研究
ー電力用遮断器の振動実験ー

国立防災科学技術センター大型実験研究部耐震実験室

稲葉誠一・木下繁夫

電力供給系に対する安全性のうち，送電系に使用される電力機器である遮断器の構造破壊について実験的研究を行なった．すなわち，発変電所に使用される72／84KV用遮断器の耐震実験を国立防災科学技術センターの大型振動台上で行なった．

実験は3波擬共振法により行なわれ，初通過規準で定義した供試体の耐震性を評価した．本報告ではN波擬共振の場合を数学的に考察して，3波擬共振の意味を明らかにし，次に実験結果と対比した．

実験の結果として，支持碍管下部の破壊が耐震性を支配し，碍管頂部における最大応答加速度でその目安が得られることがわかった．