港湾技研資料

TECHNICAL NOTE OF
THE PORT AND HARBOUR RESEARCH INSTITUTE
MINISTRY OF TRANSPORT, JAPAN

No. 817 Dec. 1995

Development of PHRI Mark II Geotechnical Centrifuge

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Development of PHRI Mark II Geotechnical Centrifuge

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Synopsis

In 1980, Port and Harbour Research Institute (PHRI) constructed the first centrifuge (Mark I) with an effective radius of 3.8 m. Since then PHRI has conducted more than 1300 centrifuge operations on various research subjects. The results of fundamental and practical research projects have been applied and reflected to the constructions of various port and harbor facilities in Japan and overseas.

Since 1989, undesirable vibrations of the concrete pit floor have frequently occurred during high speed operation of the Mark I Centrifuge. This phenomenon was accompanied with the progress of tensile cracks in the concrete pit floor. Therefore PHRI decided to construct a new centrifuge, namely Mark II, rather than repairing the Mark I Centrifuge.

In 1989, PHRI started the construction project of the new centrifuge which continued until 1994. The effective radius, maximum acceleration and maximum payload of the Mark II centrifuge are the same as the Mark I, however the control systems and safety systems have enormously improved to accommodate the 14 years' operation and experiences into the new facilities. And also the data acquisition system was totally replaced by advanced systems for the Mark II centrifuge. The Mark II centrifuge is believed to be one of the most effective and functional centrifuges in the world.

This report briefly reviews the summary of operation of the Mark I centrifuge and describes the development of PHRI Mark II centrifuge facilities.

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Development of PHRI Mark II Geotechnical Centrifuge

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要　旨

港研の旧遠心模型実験装置（Mark I）は，相似則を満足した模型実験によって，現地挙動を精度良く観察・検討する目的で昭和55年に導入された。以来，本装置を用いて港湾建設に際して遭遇する基本的な問題ならびに特定の現場で遭遇した課題の解決を目的とした研究を精力的に実施し，それらの成果は港研報告，港湾技研資料ならびに国内外の会議に発表されている。しかし，導入より10年程度経過した頃より，装置のピット床板に経年的なクラックが発生し，そのクラックの発達につれて有害な振動が運転中に発生するようになった。そのため，平成元年頃よりは最高遠心加速度を 50gに制限した条件での運転を余儀なくされ，取り組むべき数多くの研究課題に少なからぬ影響があった。

そこで，抜本的な解決を図るとともに多種多様な研究課題に対応するため，平成元年度より新遠心模型実験装置（Mark II）の建設を開始した。新装置の建設は，建設地点のボーリング調査から始まり，地下ピット及び実験棟の建設，装置機械部分の製造と据え付けならびに周辺機器の移設・整備を６ヶ年計画で実施し，平成６年度に完成した。

新遠心装置（Mark II）は，有効半径，最大遠心加速度及び最大搭載質量は旧装置と同じであるが，過去10数年にわたる経験を基に，安全面，機能面に数多くの改良を加え，また最新の技術も取り入れて製作された。そのため，本装置は国内外でも大型で最もパワフルな装置の一つであると考えている。

本報告は，新遠心装置の導入の経緯ならびに装置の基本的な諸元，周辺機器について説明を加えるとともに，新遠心装置を用いた現在の研究ならびに今後の展望についても簡潔に述べた。

なお，本資料は「新遠心模型実験装置の開発と研究への適用」（港湾技研資料 No. 812, 1995）の主要な部分を英語に翻訳したものである。

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1. Introduction

In geotechnical engineering, small-scale model tests are sometimes used to study the complex behavior of soil response and soil-structure interaction. However, it is known that soil response depends on the effective stress level within the soil mass. Therefore, small-scale model tests in a conventional gravity field of 1 g often fail to reveal some important phenomena that may exist at the prototype stress level.

To overcome this situation, it is desirable to perform a small-scale test under artificial stress level conditions. One method of doing this is the centrifuge technique, in which a small model scaled $1/n$ from the assumed prototype is tested under an "n" times gravity field created by the centrifugal acceleration. The idea of applying centrifugal acceleration to model testing was said to be originally proposed by French engineer Phillips in 1869. The idea was put into practice by Bucky in 1931 in USA and by Pokrovsky and Davidenkov at around the same time in USSR. Principle of geotechnical centrifuge modeling has been appreciated since the 1930s and explained by several research workers[1]. At present, centrifuge model testing has become an important tool for investigation of complex geotechnical problems as referenced by several recent symposia around the world.

Currently more than five dozens geotechnical centrifuges are in operation in various countries. In Japan Prof. Mikasa at Osaka City University was the first who built a centrifuge with an effective radius of 1.01 m in 1965 and utilized it to study the consolidation process of soft clay. In the 1960s, Tokyo Institute of Technology (TIT) built a larger centrifuge with an effective radius of 1.18 m. These two centrifuges were employed extensively to investigate the self-weight consolidation, the bearing capacity of soil and so on. These research efforts and achievements proved the importance of centrifuge model testing in geotechnical engineering.

In 1980, Port and Harbour Research Institute (PHRI) constructed the first centrifuge (Mark I) with an effective radius of 3.8 m. For typical prototype structures in port and harbor areas, a reasonable soil area to be modeled was considered to be 150 m by 150 m in plane. Therefore, the effective radius of 3.5 m, the maximum acceleration of 100 g and the swinging platform of 1.5 m by 1.5 m were decided for the PHRI Mark I centrifuge. This provided insight for many research engineers in Japan with motivation to build up their own centrifuges.

Since then PHRI has conducted more than 1300 centrifuge operations on various research subjects. Some of them were related to basic research topics such as investigating the bearing capacity of shallow foundations on sandy or clayey grounds, behavior of a single pile under lateral loads, and so on. Because the Ministry of Transport is in charge of constructing port facilities in Japan, our research activities also included practical research project associated with specific prototypes. These research results relating to the centrifuge model tests have been published in various technical journals and reports for specific construction offices. The results of these fundamental and practical research projects have been applied and reflected to the constructions of various port and harbor facilities in Japan and overseas.

Since 1989, undesirable vibrations of the concrete pit floor have frequently occurred during high speed operation of the Mark I Centrifuge. This phenomenon was accompanied with the progress of tensile cracks in the concrete pit floor. From detailed investigations it was found that the undesirable vibration was due to the fatigue failure of the concrete pit and structural defects in machine layout. Therefore maximum operative acceleration was limited below 50 g for safety reasons, which in fact led to serious limitation to research projects to be studied.

Consequently, PHRI decided to construct a new centrifuge, namely Mark II, rather than repairing the Mark I Centrifuge. In the planning for the Mark II centrifuge, statistical studies were carried out on the actual operating acceleration levels and the volume of soil specimen used in the 14 years' Mark I centrifuge operations. As a result of this study it was found that the major dimensions and capacities of the new centrifuge to be the same as the Mark I Centrifuge. Therefore, the main arm and the swinging platforms of the Mark I centrifuge were used again for the new centrifuge.

The construction project of the Mark II centrifuge facility included ground survey, construction of underground concrete pit, new buildings and centrifuge machine, and up-grading the ancillary equipment. In 1989, PHRI started the construction of the new project which continued until 1994, based on the financial support provided by Japanese government. During these six years' construction period the Mark I centrifuge had been operated as usual below the limited acceleration. The effective radius, maximum acceleration and maximum payload of the Mark II centrifuge are the same as the Mark I, however the control systems and safety systems have enormously improved to accommodate the 14 years' operations and experiences into the new facilities. And also the data acquisition system was totally replaced by advanced systems for the Mark II centrifuge. The Mark II centrifuge is believed to be one of the most effective and functional centrifuges in the world. The construction project for the Mark II centrifuge facility was completed in 1994. Since then many research projects related to model testing have been performed in the Mark II centrifuge.

This report briefly reviews the summary of operation of the Mark I centrifuge and describes the development of PHRI Mark II centrifuge facilities.

2. Operation of PHRI Mark I Centrifuge

2.1 Machine use

The construction of the Mark I centrifuge (**Fig. 1**) began in 1977 and completed in March of 1980. Since then PHRI has conducted more than 1300 centrifuge operations and has published nearly 60 papers related to centrifuge model tests. The basic configuration of the centrifuge machine and its assembly have been described by Terashi[2),3)]. Since the operation of the Mark I centrifuge was already reported in detail[4)], only a brief summary is presented here.

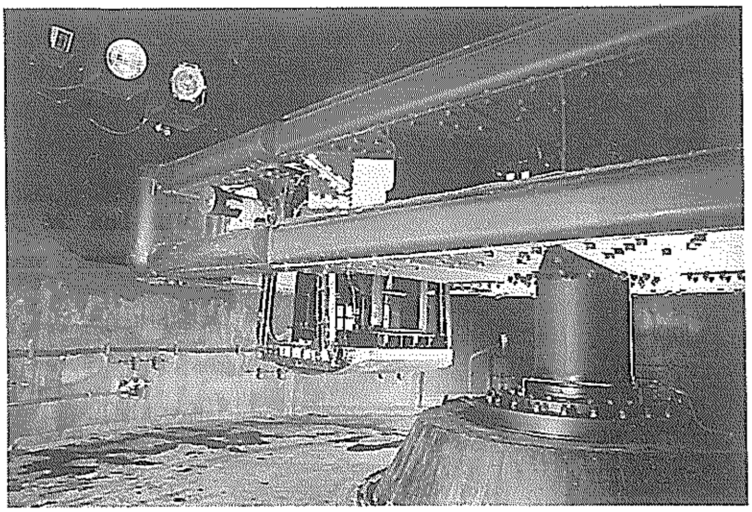


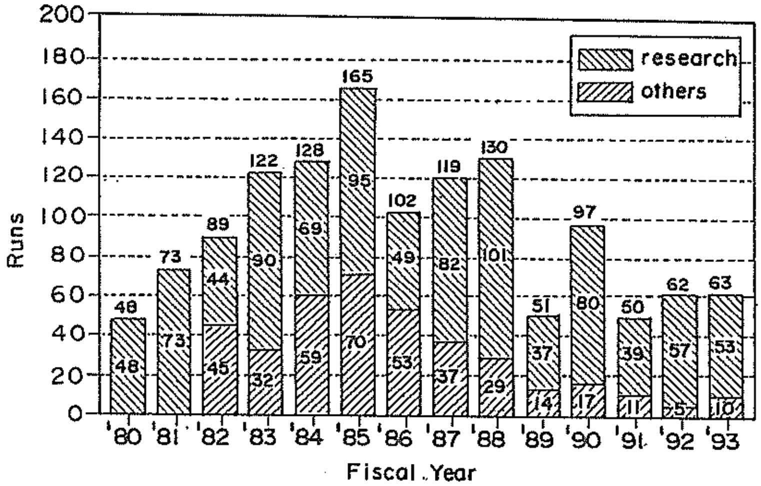
Fig. 1 PHRI Mark I Centrifuge

The centrifuge efficiency can conveniently be assessed in terms of the number of machine runs, total running hours and total running machine rotations within a particular period of time. **Figure 2** shows the statistics of operating the Mark I centrifuge within 1980 to 1994. The analyses indicate, on a yearly basis, the average usage over an 14 years period of 93 runs totaling 229 hours per year. Of the total number of machine runs over this period some have yielded successful geotechnical data; the remainder fall into a non-productive category including machine testing, instrument calibration, equipment proving, and tests which have been discarded for different reasons. **Figure 2** (a) shows the two categories of the machine runs. It can be seen that 25 percent of the machine runs fall into the non-productive machine runs. This ratio is almost in the same order as that of the centrifuge machine of Manchester University[5] in England.

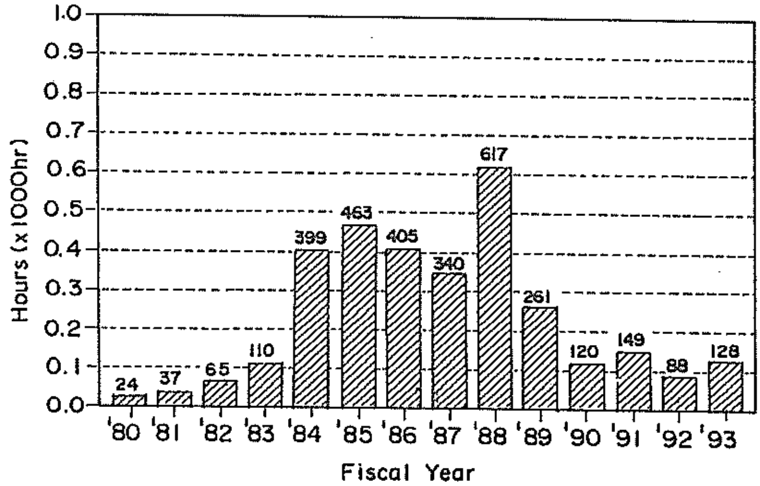
Up to 1983 use of the centrifuge was mainly on evaluating the bearing capacity of sandy ground. Since this subject was a first model test for PHRI centrifuge, fairly simple model tests, concentric loading tests, were carried out at beginning. Know-how on operating the centrifuge, model preparations as well as model test procedures have been accumulated during a large number of repeated tests.

From 1984 the involvement with research on cohesive material required a long-run centrifuge operation for obtaining normally consolidated clay ground having the shear strength increases with depth to simulate the soil profile condition in most harbor areas in Japan. A clay often used in the model tests was Kaolin clay whose coefficient of consolidation was relatively large so that consolidation time required for self-weight consolidation in a centrifuge could be reduced to one and half days for the clay ground of 20 cm in thickness. For safety operation almost all staff members including the main investigator carefully monitored both the machine and the model ground during the long-run operation. Model ground preparation using cohesive materials have been governed not only by consolidation period but also by personnel exhaustion in the long-run operations. Therefore, the model tests on cohesive materials were carried out about once or twice a month and relatively short runs were carried out in the intervals of the long-run operation.

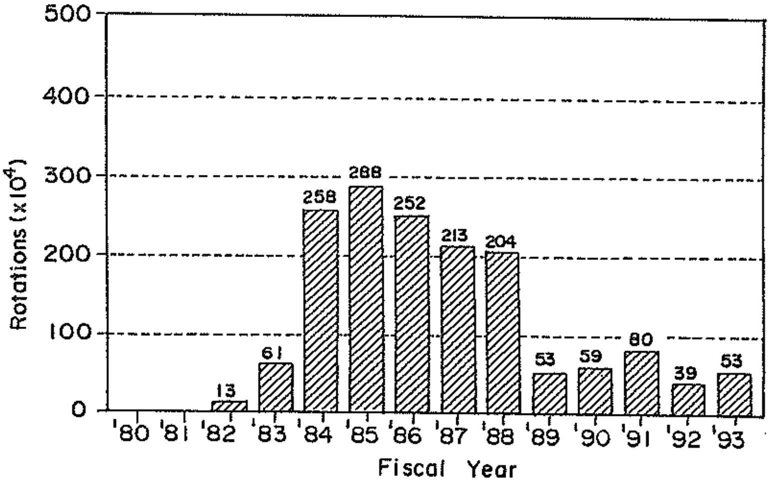
Since 1989, undesirable vibration of the concrete pit floor was occurred at high speed operation. This phenomenon was found to be due to the progress of fatigue cracks in the concrete pit. After detailed investigations and discussions with the manufacturer, the maximum operative acceleration of the centrifuge was limited to 50 *g* for short-run and 40 *g* for long-run experiments for safety reasons.



(a) operation runs



(b) operation hours



(c) operation rotations

Fig. 2 Annual breakdown of centrifuge usage over an 14 years period (1980-1994)

2.2 Safety

An annual maintenance and a set of regular inspections contributed to the safe operation of the centrifuge for the last 14 years. The annual maintenance of about two weeks was undergone by the manufacturer to check the machine hardware components, electric systems, lubrication and so on. Since 1989, vibration of the concrete pit and progress of the cracks in the pit were also monitored during the annual maintenance.

The centrifuge was operated under a set of safety regulations, designed to minimize the risk of accidents to the personnel and peripheral equipment. Model specimen boxes were designed using three dimensional elastic finite element analysis to ensure the structural soundness and to confirm the amount of expansion of the box during the flight within the allowable values. All boxes thus designed and manufactured were subjected to proof testing in advance up to 20 percent higher acceleration than the acceleration of commonly use. In the proof tests, the deformation and the strain of the box were measured at various points and confirmed to remain within the allowable values. After these procedures, the boxes could be in use for model testing.

In model testing, the weight and eccentricity of model components and its counterweight are checked in advance, using on-flight authorization sheets, to meet a balance requirement aimed at limiting overload on the machine bearings as a more strict requirement than that of overall structural integrity. When models are mounted on the swinging platform of the centrifuge, all the equipment, transducers as well as loading devices are carefully examined in the presence of the responsible engineer.

During the operation of centrifuge a continuous check is made on potential off-balance loads, temperature increase, and noise in the rotary joints and bearings, and the vibration of the machine and concrete pit. These vigorous inspection procedures have tremendously contributed to the safe operation of the centrifuge for the last 14 years.

2.3 Research subjects studied

Figure 3 and **Table 1** indicate the area of research subjects conducted over the last 14 years. These projects which are either curiosity oriented and a foundamental research include the investigation of bearing capacity of foundation on sandy ground or normally consolidated clayey ground, reinforcement of embankment by geotextile, horizontal resistance of a pile and failure behavior of the improved grounds using sand compaction pile (SCP) method and deep mixing (DM) method. The research topics listed in **Table 1** oriented and have close relevance to specific prototypes. These research activities have contributed for better understanding of prototype behavior and improvement of the current design procedures. The details of each subject have been presented in different publications[6)-43)].

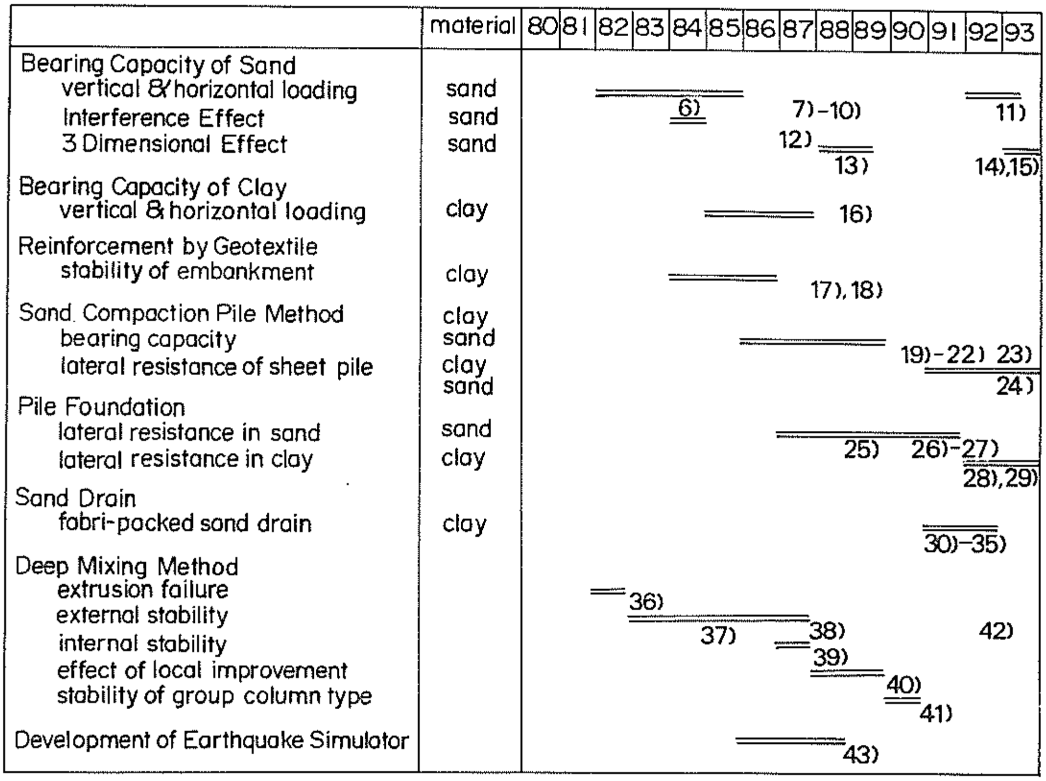


Fig. 3 A chronology of research subjects using centrifuge apparatus

Table 1 Practical research subjects using centrifuge apparatus

	Research Topic	Soil Improvement	Period
Niigata Port	Application of DMMethod to retaining wall	Deep Mixing Method	'92～'93
Haneda Airport	Stability of retaining wall due to excavation		'87
	Application of fabri-packed sand drain to extremely soft clay ground	Sand Drain	'91
	Influence of embedded sheet wall pile to deformation of ground surface		'93
Wakayama Shimotsu Port	Effect of local soil improvement on the behavior of revetment	Deep Mixing Method	'89
Osaka Port	Effect of SCP improvement on slope stability	Sand Compaction Pile Method	'90
Kumamoto Port	Deformation of soft ground under placement of soft-landing break waters		81

2.4 Causes of vibration

As mentioned before, the undesirable vibrations of the concrete pit floor of the Mark I centrifuge have frequently occurred since 1989, which required continuous effort to clarify the sources of the vibration, to monitor the progress of crack propagation, and to find suitable countermeasures for safe operation of the centrifuge. According to detailed investigations, based on the settlement data of the concrete pit floor, measurement of vibrations, and the analyses of several parts of the machine and the floor, it was found that the vibration was induced by the fatigue failure of the concrete pit floor. The extension of many tensile cracks observed at the exterior side of the pit proved that the concrete pit floor was gradually sinking by its self-weight (as shown in **Fig. 4**) and it leaned toward the main rotating shaft. The thermal expansion of the main shaft during the long-run experiments reduced the gap between the gear engagements and aggravated the vibration. In addition, the structural members in which the rotary joint, rotary transformer and slip rings were installed on the upper side of the main shaft, as shown in **Fig. 4**, caused harmful effects and contributed to the vibration of these equipment. As a result, PHRI authorities decided to construct a new centrifuge rather than repairing and improving the Mark I centrifuge.

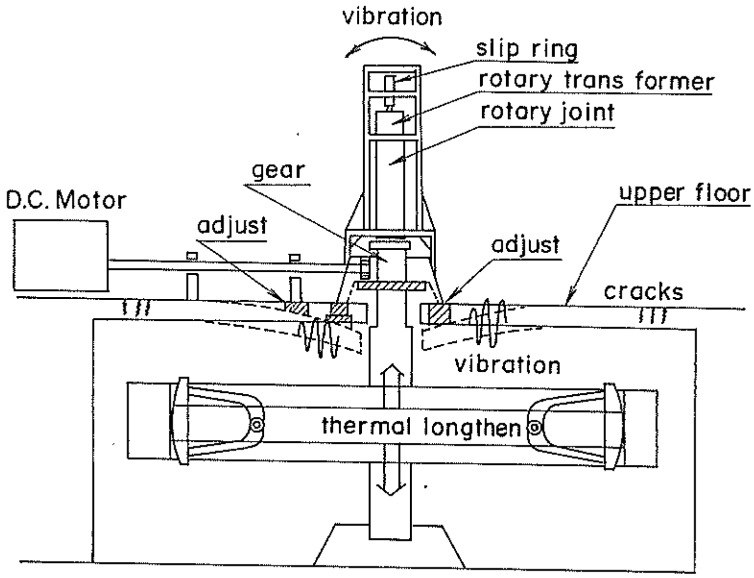


Fig. 4 Schematic layout of the Mark I centrifuge

3. Development of PHRI Mark II Centrifuge

3.1 Layout of the centrifuge facility

The development of the PHRI Mark II centrifuge facility was started in 1989, in which new centrifuge apparatus, new centrifuge building, model preparation building and operation building were also constructed. **Figure 5** shows the layout of the new centrifuge facility. These buildings and centrifuge apparatus were constructed according to the time table shown in **Table 2** based on the grant furnished by Japanese government.

The new centrifuge building housing the Mark II centrifuge (**Figs. 6** and **7**) was constructed adjacent to the Mark I centrifuge building which is presently used as the model preparation

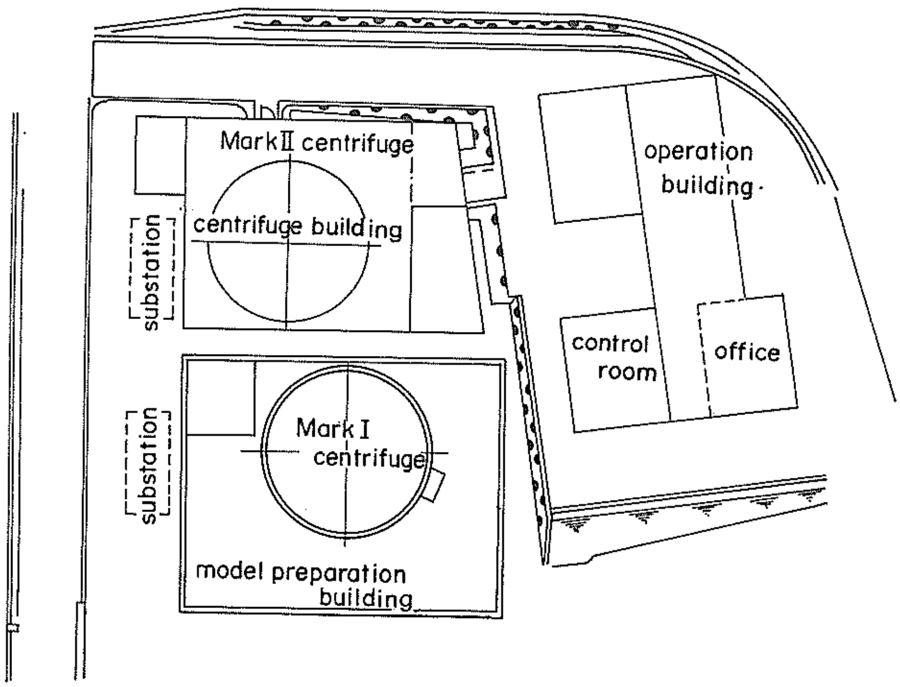


Fig. 5 Schematic layout of the Mark II centrifuge facility

Table 2 Time table of the construction project

	'89	'90	'91	'92	'93	'94
1. Soil Survey	═					
2. Construction of MarkII centrifuge						
① substation				═		
② machine				═	═	═
3. Construction of Concrete Pit						
① excavation	═					
② concrete pit		═				
4. Constructions of buildings						
① model preparation building						═
② new centrifuge building		═	═			
③ operation building	═	═	═			

building, as shown in **Fig. 5**. This building is consisted of an underground concrete pit, electricity supply room, and a crane to transport the specimen boxes.

The centrifuge operation building, the former training center of the institute, was remodeled to a number of offices and control room. And two bed rooms and shower room were also prepared for the convenience of the personnel during the long-run experiments of the centrifuge. Therefore, the model preparation and centrifuge control can be conducted separately from the centrifuge machine which will prevent human damage in case of serious accident of the machine.

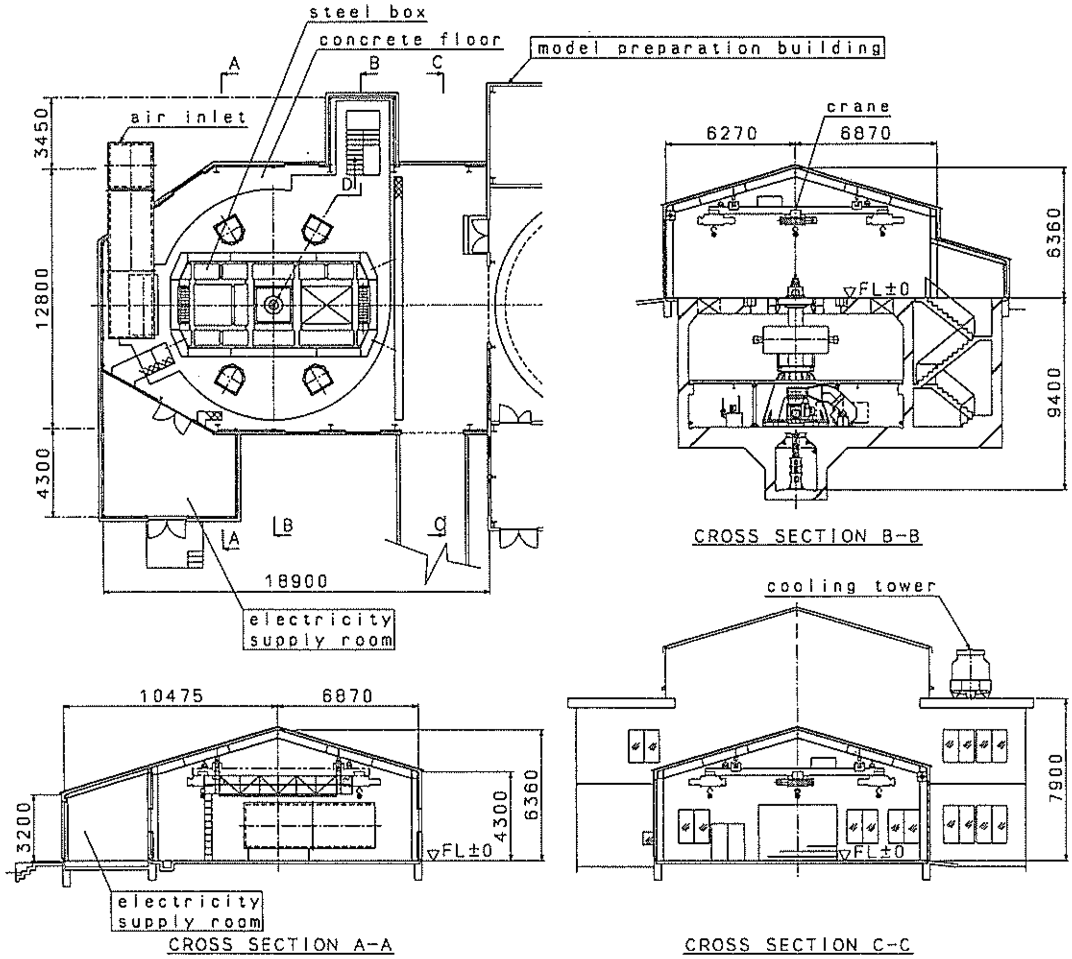


Fig. 6 New centrifuge facility

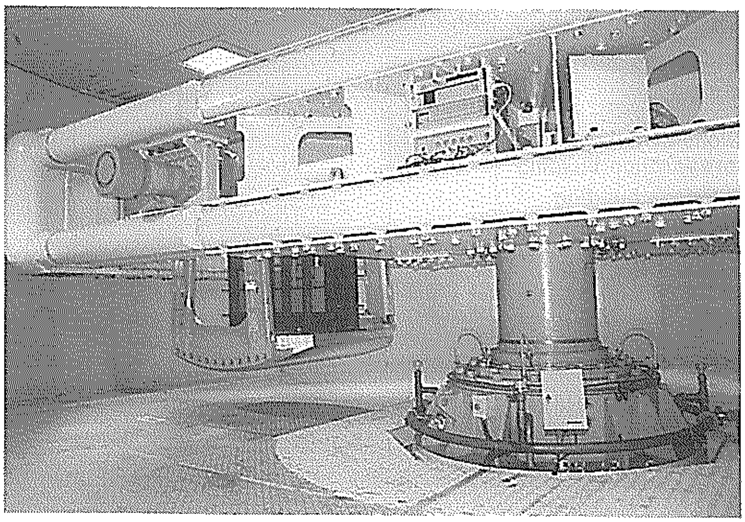


Fig. 7 Photograph of PHRI Mark II Centrifuge

3.2 Concrete pit

The underground concrete pit for the Mark II centrifuge was constructed by digging down soft rock 9.4 m below the ground level, as shown in **Figs.** 8 and 9. The reinforced concrete pit has a sufficient large thickness wall of 50 cm to resist against the earth and water pressures from the surrounding ground and potential radial unbalance force during the centrifuge operation.

The concrete pit has three floors under the ground. The top floor of the pit has the same elevation as that of the model preparation building so that specimen box can be easily transported

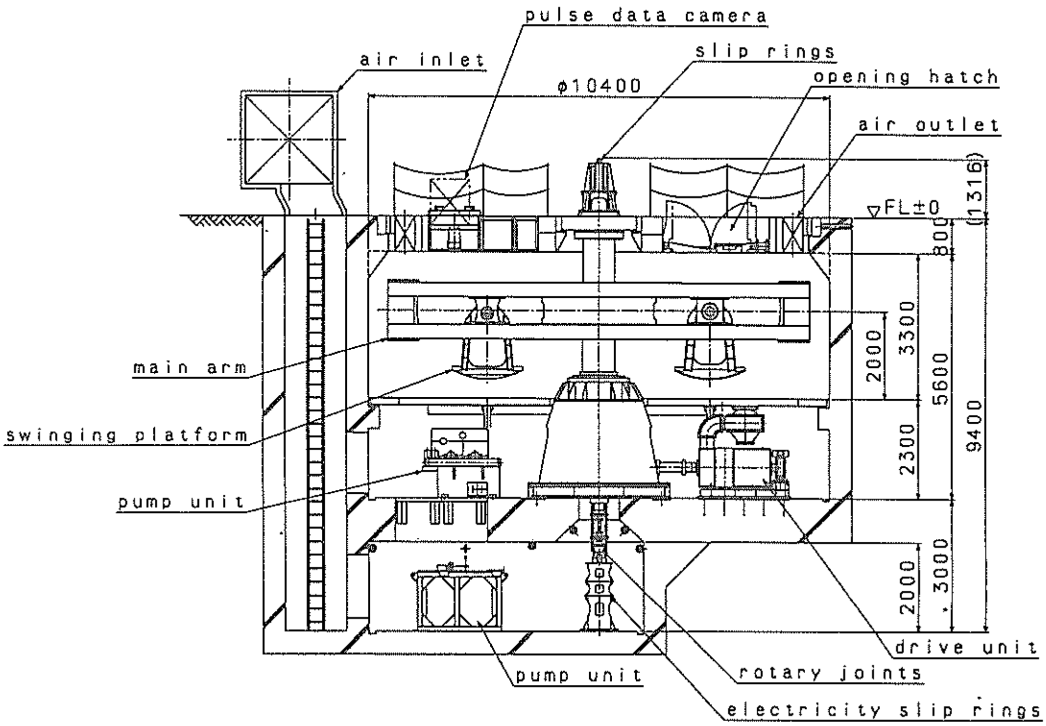


Fig. 8 Reinforced concrete pit and centrifuge machine

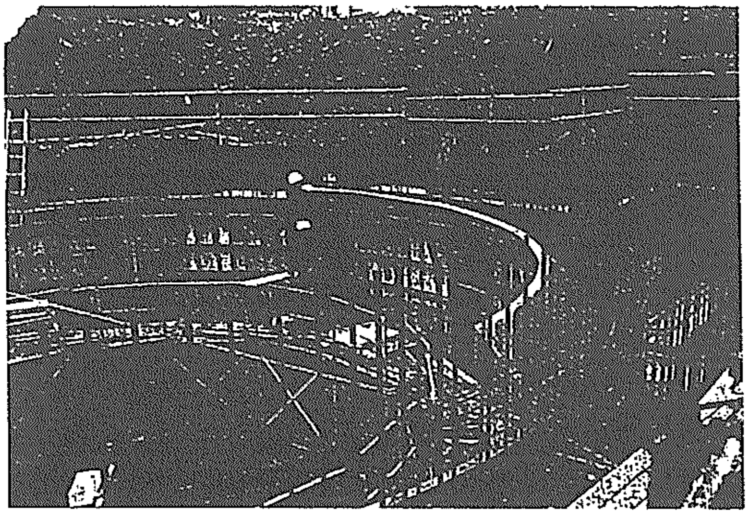


Fig. 9 Construction of reinforced concrete pit by handcart from or to the model preparation building. The floor is composed of the concrete slab of 80 cm in thickness and steel box in its central part, as shown in **Fig. 6**. The steel box, which is lighter than concrete, can help to prevent any possible settlement of the floor which was observed in the Mark I centrifuge. And the box can be removed entirely so that the centrifuge machine can be lifted up without disassemble of the system in the case when entire repair is needed. A hydraulic driven opening hatch and a perspex window are also installed in the steel box for transporting specimen box to the centrifuge and for the 70 mm pulse-data camera, respectively. Six outlets are prepared in the upper floor to control the air circulation in the pit. Many fluorescent lamps are also installed in the box for lighting up the 1st basement of the pit.

The 1st basement of the pit, 10.4 m in diameter and 3.3 m in height, which houses the main part of the centrifuge. A set of three windows is allocated on the side wall of the 1st basement for the 70 mm pulse-data camera. Furthermore, plug sockets and jack plugs for inter-phone connection to the control room are affixed on the side wall, along with the outlets of air and water pressures and vacuum for ease of model preparation. Almost all the periphery equipment such as fluorescent lamps, observation cameras and outlets for electricity and hydraulic pressures are installed outside the spinning zone of the centrifuge arm, but within the concrete pit, in order not to be affected by the air flow induced during the operation of the centrifuge.

The driving unit and the hydraulic pump unit for lubrication of the upper and lower gears of the main shaft are installed in the 2nd basement, along with the plug sockets and jack plugs for the inter-phone.

The 3rd basement has comparatively small sectional area in which the lubricating pump unit, the electric slip ring for supplying AC electricity, and rotary joints are installed on the bottom of the main shaft.

3.3 General configurations of the centrifuge

As mentioned earlier the PHRI Mark II Centrifuge has the same capacity as the Mark I with a maximum acceleration of 113 *g*, maximum pay load of 2,760 kg and maximum capacity of 300 *g-tons*. Major specifications of the centrifuge machine and its ancillary equipment are listed in **Table 3**. The Mark II centrifuge, in comparison with other centrifuges operating in different countries, is ranged among the high capacity centrifuges in the world, as shown in **Fig. 10** and **Table 4** [40-63].

(1) basic layout

The main part of the centrifuge is housed in the underground reinforced concrete pit for safety operation as shown in **Figs. 7** and **8**. The main part of the centrifuge weighs approximately 87 tons and consists of an arm, 9.65 m in diameter, and two swinging platforms which are hinged to the rotating arm via the torsion bar systems to safely deliver the radial force at high acceleration to the end plates at both ends of the arm. This system was originally developed in Cambridge University [1] in England and installed in the Mark I centrifuge.

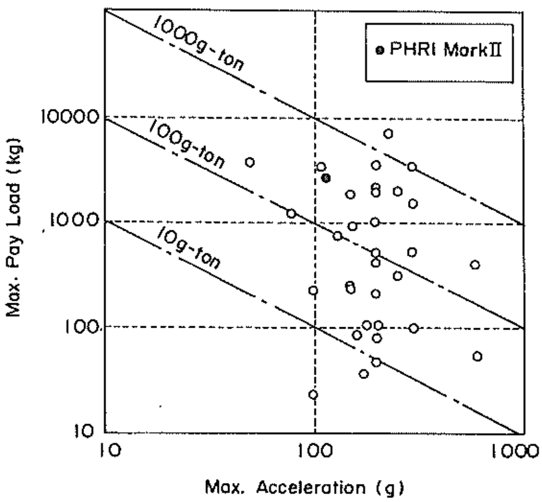


Fig. 10 Comparison of capacity

Table 3 Major specifications of the Mark II centrifuge

maximum acceleration		113 *g*
maximum number of rotation		163 *rpm*
maximum pay load		2,760 *kg*
diameter of rotating arm		4.757 *m*
maximum effective radius		3.8 *m*
maximum capacity		300 *g-tons*
space of swinging platform		1.6 *m* by 1.6 *m*
main motor		440 *V* (DC)
		450 *kW*

rotary joints			
	oil	max. pressure	210 kgf/cm^2
		max. flow	60 *l/min*
		number of ports	2 ports
	water	max. pressure	10 kgf/cm^2
		max. flow	120 *l/min*
		number of ports	2 ports
	air	max. pressure	10 kgf/cm^2
		max. flow	120 *l/min*
		number of ports	1 port
electricity slip ring			
		capacity	AC 200 *V*, 30 *A*
		number of channel	4 channels
slip ring			
		capacity	AC 100 *V*, 1 *A*
		number of channels	44 channels
optical fiber rotary joints			
		number of channels	15 channels

(2) main shaft

The main shaft of the centrifuge, as shown in **Fig. 11**, has a maximum diameter of 1.2 m and 3.41 m in length, and has been designed to endure the radial unbalance forces of 37 tons in usual flight and 77 tons in emergency. The shaft is supported at its both ends by bearings for safety operation. The bottom bearing was designed to support both radial and thrust forces and the upper bearing was designed to support radial force. This bearing system was adopted based on the experience of the Mark I centrifuge, which can prevent any restriction of the axial expansion of the main shaft due to temperature increase at the upper bearing. **Figure 11** also shows the cross section of the main shaft in which four holes for data acquisition and six holes for hydraulic pressures are bored in the jacket of the main shaft.

(3) main arm and swinging platform

The main arm is composed of four frames, bridge plates and end plates, as shown in **Fig. 12.** The main arm is tightly fixed to the main shaft by screw bolts. Two swinging platforms are hinged to the arm via the torsion bar systems as shown in **Fig. 13**. The gap between the end plate and the bottom of the swinging platform, when lifting up the swinging platform at 1 *g*, is designed to be 1.2 mm which corresponds to the swinging platform with pay load of 1000

Table 4 Major centrifuges in the world

No.	Institution	Country	Max. Radius (m)	Effective Radius (m)	Max. Accel. (g)	Max. Payload (kg)	Capacity (g-ton)
1	The University of Western Australia	Australia	1.8	1.55	200	400	40
2	C-CORE	Canada	5.5	5	200	2200	220
3	Chengdu Hydroelectric Investigation and Design Institute	China		10.8	110	3000	216
4	Hehai University	China		2.4	250		25
5	Institute of Water Conservancy and Hydroelectric Power Research	China	3		300	1500	450
6	Nanjing Hydraulic Research Institute	China	3	2	200	100	20
7	Nanjing Hydraulic Research Institute	China		5	200	2000	400
8	Yangtze River Science Research Institute	China	3.47	3	300	500	150
9	Danish Engineering Academy	Denmark		2.3	80	1200	96
10	CESTA	France	10				
11.	LCPC	France	5.5	5	200	2000	200
12	City University	UK	1.8	1.55	200	400	40
13	Lucas Aerospace Division	UK	2.6				
14	UMIST	UK		1.5	133	750	100
15	University of Cambridge	UK	4.3	4	155	900	
16	University of Liverpool	UK		0.991	200	200	20
17	University of Manchester	UK	3.2		200	3400	
18	Ruhr-Univ.	Germany		4.125	250	2000	500
19	Ruhr-Univ.	Germany	1.8	1.55	200	400	40
20	Delft University of Technology	Holland			300	3500	
21	Israel Defence Ministry	Israel	1.5		100		
22	ISMES	Italia			600	400	
23	NIKKEN SEKKEI	Japan	3	2.7	200	1000	100
24	Port and Harbour Research Institute, Mark-1	Japan		3.8	115	2710	300
25	Kyoto University	Japan		1.5	200		
26	Ministry of Construction	Japan		1.15	300		
27	Kashima Co.	Japan	3	2.7	200	1000	100
28	Osaka City University, Mark-5	Japan		2.56	200		22.4
29	Taisei Co.	Japan		2.65	200	400	80
30	Chuo University	Japan	3.05		180	100	
31	Tokyo Institute Technology, Mark-2	Japan		1.25	150	250	37.5
32	Toyo Construction	Japan		2.2	250	300	75
33	Ministry of Labor	Japan	2.31		200	500	
34	Hydroproject Institute	Russia	2.5		320		
35	Institute of Ukr.N.I.I. Projekt	Russia		2.505	320		
36	Research Institute of Bases and Underground Structures	Russia	2		100		
37	VNII Vodgeo	Russia		2.3	250		
38	National University of Singapore	Singapore					
39	Boeing Aerospace Company	USA	1.4		600	55	66
40	Bureau of Mines at Maryland	USA	0.9				
41	California Institute of Technology	USA	1.3		175	36	7.5
42	MIT	USA			200	68	15
43	Missouri School of Mines at Rolla	USA	1.07				
44	New Mexico Engineering Research Institute	USA	1.8		100	227	25
45	Princeton University	USA	1.3		200	76	10
46	Rensselar Polytechnic Institute	USA	3	2.7	200	1000	100
47	Sandia Corporation: CA-2	USA	2.1		150	227	15
48	Sandia Corporation: fixed	USA	7.62		240	7257	800
49	Sandia Corporation: swing	USA	7.62		150	1814	300
50	US Air Force Engineering and Services Center	USA	1.83		100	225	15
51	University of California at Davis	USA		9.1	50	3640	275
52	University of California at Davis	USA	1		175		5
53	University of Colorado at Boulder	USA	5.49		200	2000	440
54	University of Colorado at Boulder	USA	1.36		300	100	15
55	University of Florida: A	USA	1		100	22.7	2.5
56	University of Florida: B	USA	2		160	83.9	
57	University of Maryland	USA	1.34		200	45.4	10

kg should touch down on the end plate of the arm at 40 g. On the central part of the main arm the switching box, amplifier, A/D convertors, as well as hydraulic accumulators are appended, as shown in **Fig. 14**.

On the surface of the swinging platforms many threaded holes have built in, as shown in **Fig. 15**, so that various kinds of specimen boxes with different dimensions and loading devices are easily mounted on, in supplement to the terminals for data acquisition, electricity and hydraulic outlets.

(4) drive unit

The drive unit for the Mark II centrifuge of 450 kW DC motor is mounted on the 2nd basement floor of the pit as shown in **Figs. 16** and **17**. This unit steadily increases the acceleration of the centrifuge up to 113 g, as shown in **Fig. 17**. The drive unit also functions as a reverse

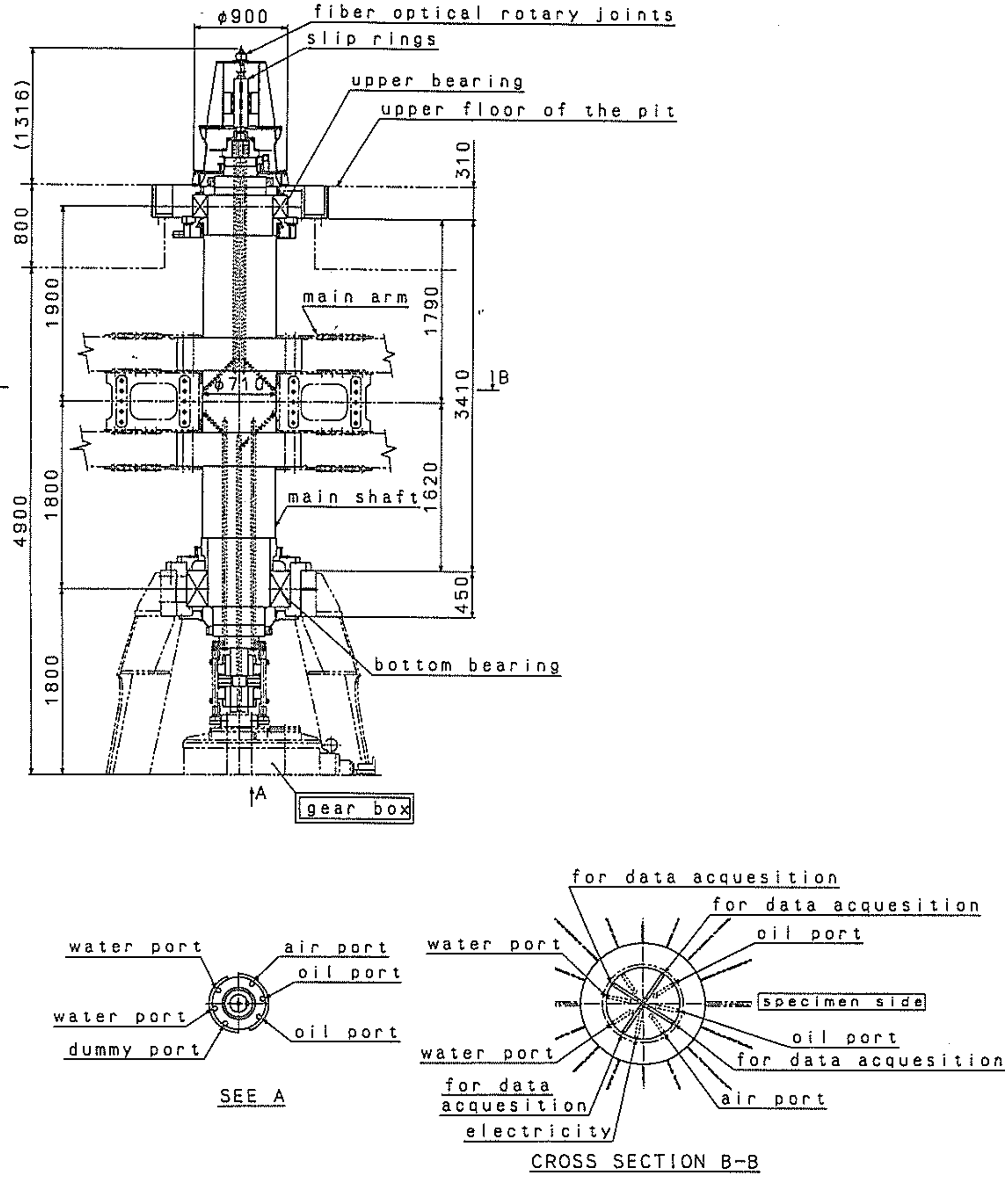


Fig. 11 Main Shaft

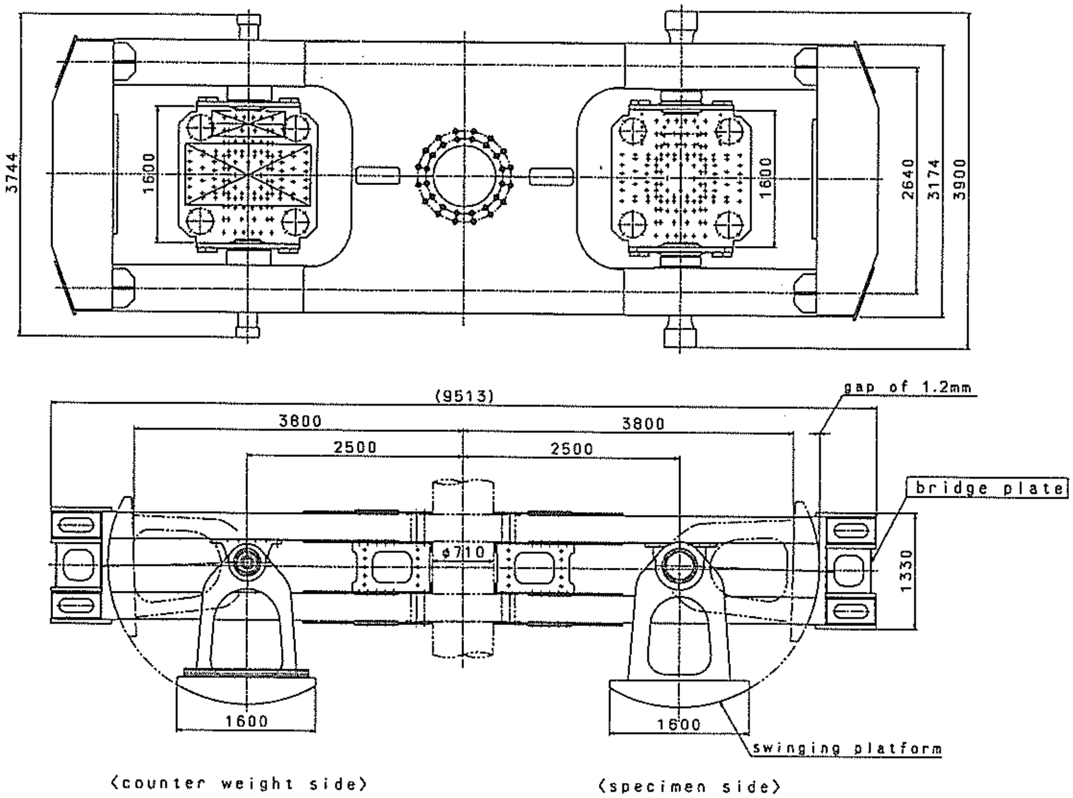


Fig. 12 Main arm

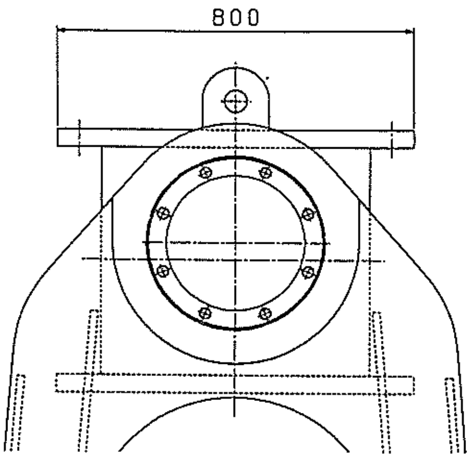


Fig. 13 Torsion bar system

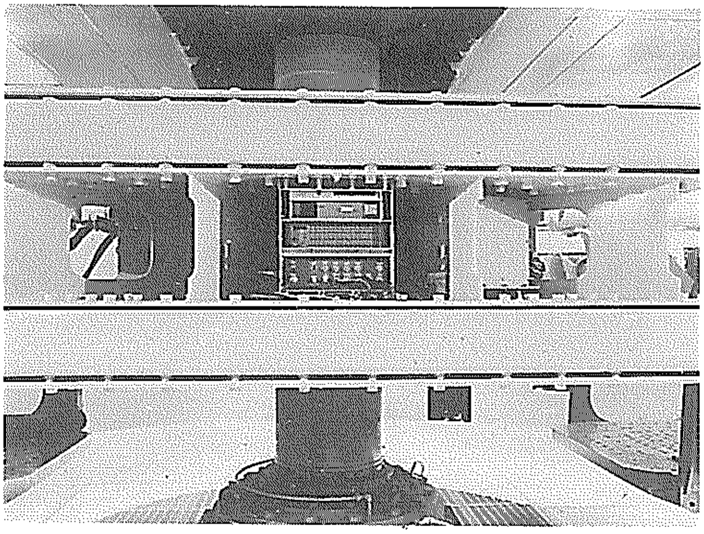


Fig. 14 Amplifier and A／D convertors on the main arm

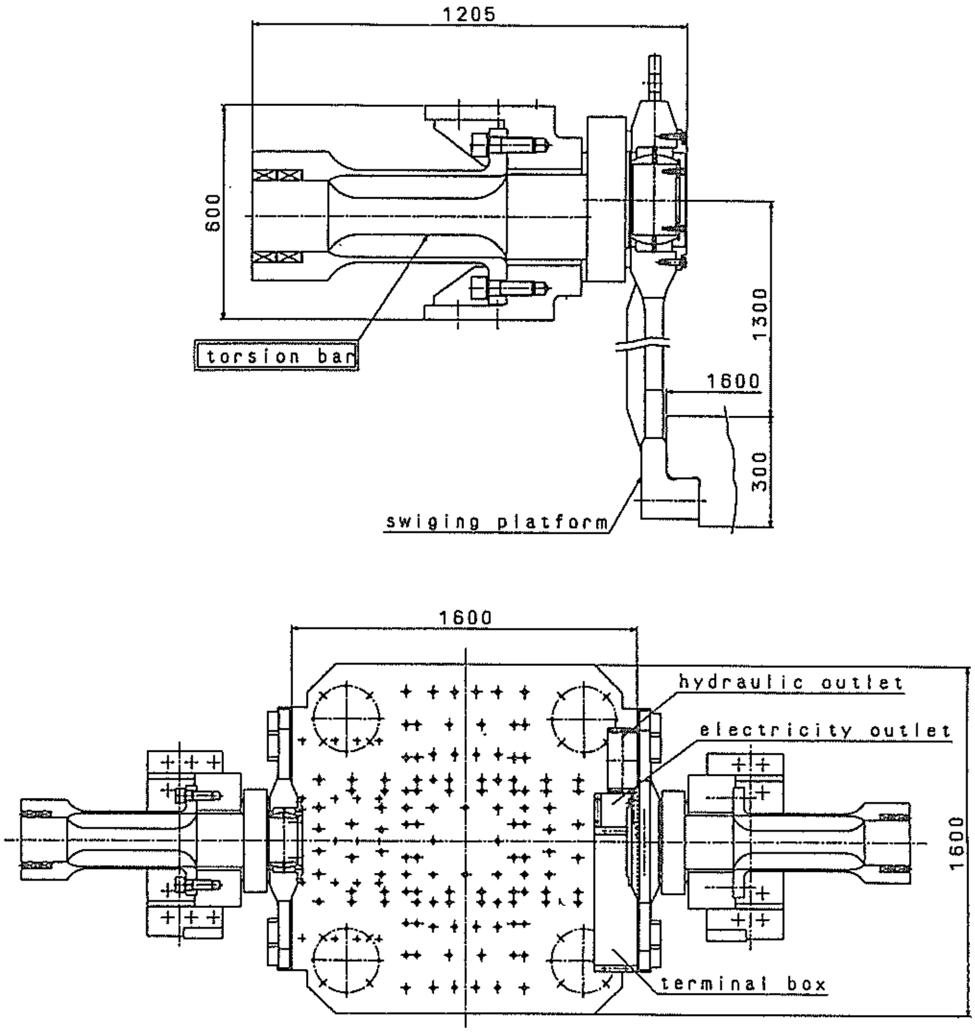


Fig. 15 Swinging platform

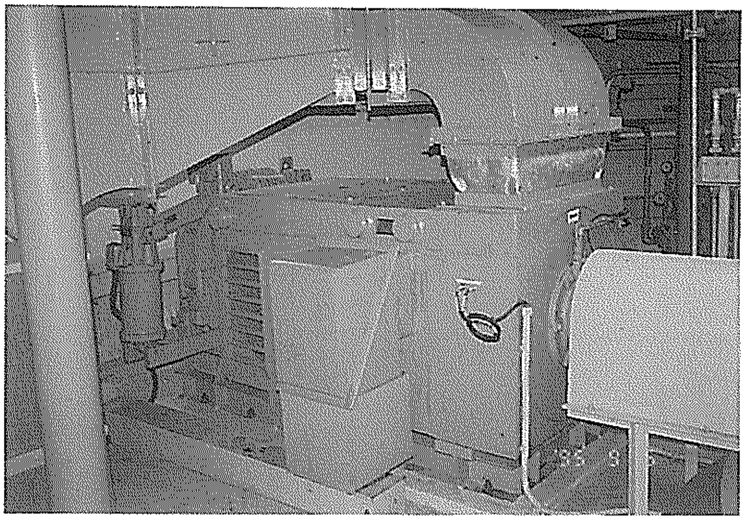


Fig. 16 Drive unit

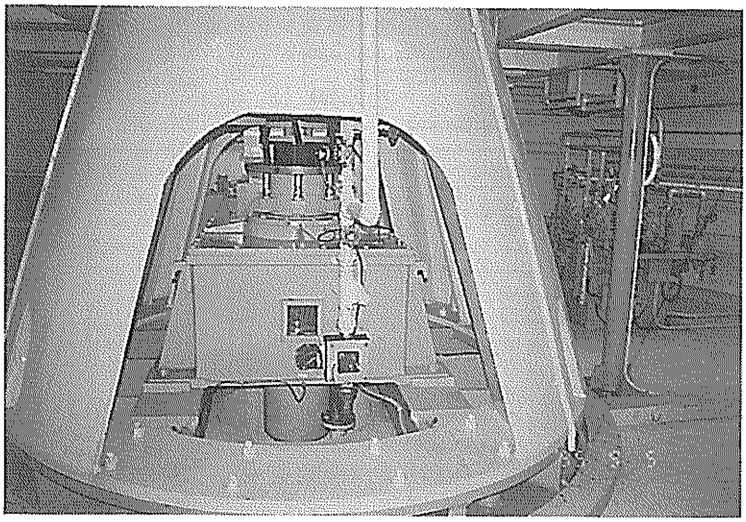


Fig. 17 Gear box

generator during deceleration of the centrifuge which enables the centrifuge to stop within 15 minutes by exhausting the inertia energy of the machine.

(5) Lubrication unit

The pump units shown in **Figs. 18** and **19** were installed on the 2nd and 3rd basement floors of the pit. These units are designed to circulate the oil at 85 liters per minute to the gear box and to the two bearings for continuous lubrication. In the case of electricity failure the machine may take about two hours to fully stop because the drive unit can not exhaust the energy. However, the lubrication of the gear and the bearings should be maintained until the machine fully comes to stop. Therefore an emergency generator unit as shown in **Fig. 20**, was also installed for the pump units in the case of electricity failure during the experiment.

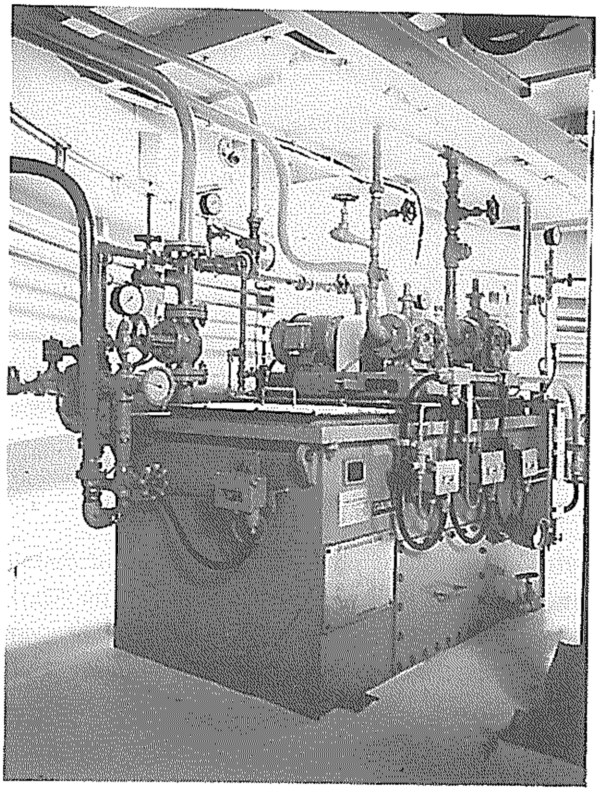


Fig. 18 Pump unit for oil supply

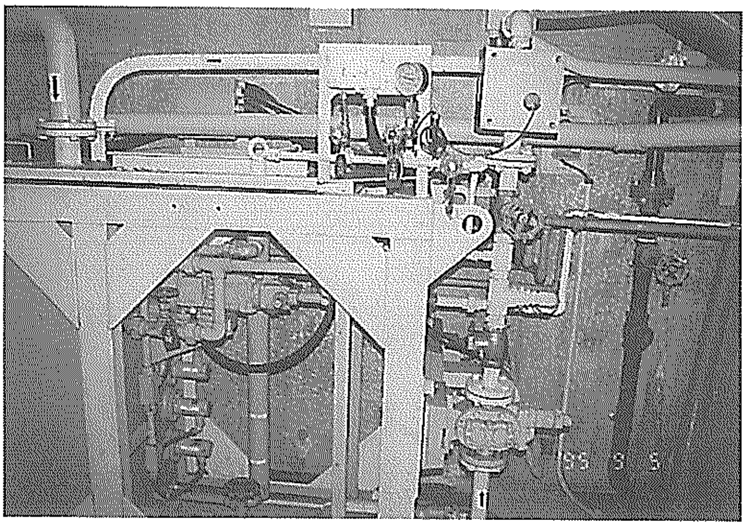


Fig. 19 Pump unit for oil return

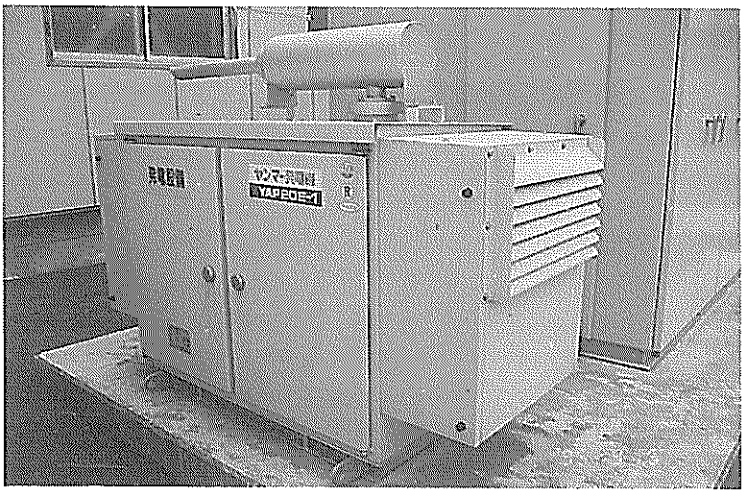


Fig. 20 Emergency generator for lubrication

(6) air circulation

All the energy dissipated during the aerodynamic heat losses of centrifuge operation raises the temperature of the air mass contained in the centrifuge pit. In the Mark I centrifuge an air conditioner was installed on the top floor of the pit to cool the air against the temperature increase caused by the spinning of the centrifuge[2),3)], but it did not have enough capacity to cool the air sufficiently. Therefore, in the Mark II centrifuge air in the pit is continuously replaced by fresh air when the centrifuge is on operation, as shown in **Fig. 21**. A large scale air inlet is installed in the concrete pit to allow fresh air flow into the 1st basement through the 2nd and 3rd basements. Six outlets are furnished in the top floor of the basement to deplete the air in the pit.

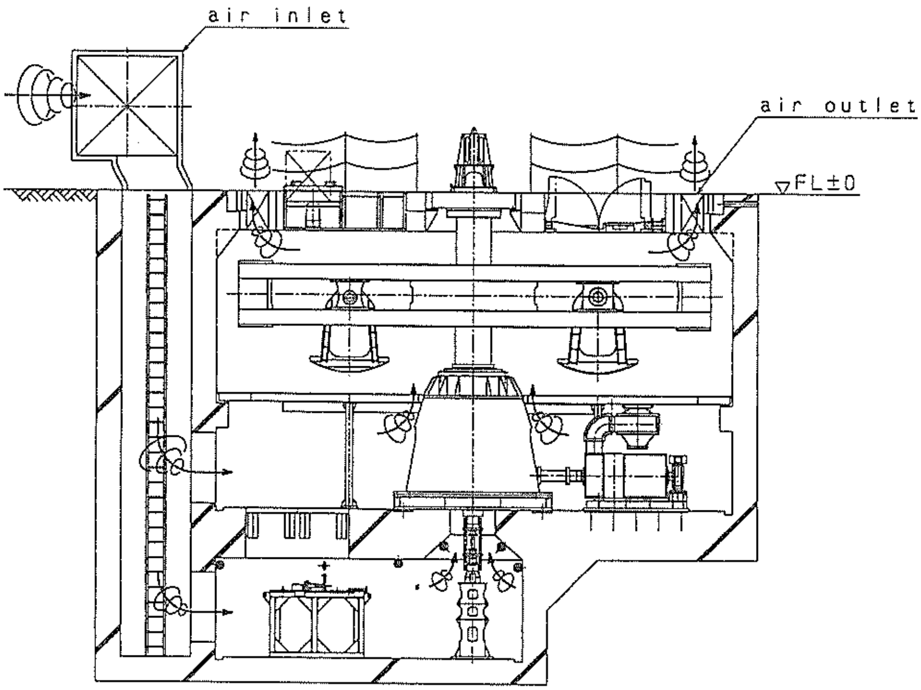


Fig. 21 Air Circulation

(7) operation system

The operation of the centrifuge is conducted using the control panel in the control room of the operation building, as shown in **Fig. 5**. **Figure 22** indicates the control panel and the operation desk which control the whole operation process of the centrifuge and monitor the safety systems. Conditions of all the important components of the centrifuge, such as upper and bottom bearings of the main shaft, electric currents, lubrication, the vibration at the pit and gear box, and so on, are simultaneously monitored by closed-circuit systems and are displayed on the control panel screens. The control panel is equipped with safety measures to activate the alarm system on emergency situations by halting the machine automatically. All the data monitored in the system are automatically recorded in optical disk in case of trouble for ease of investigation of the cause of the system failure. In addition, to ensure human safety and optimized operation, the centrifuge facilities are equipped with a safety management system that includes several T.V. cameras, monitors, locks, detectors, emergency switches, and inter-communication system.

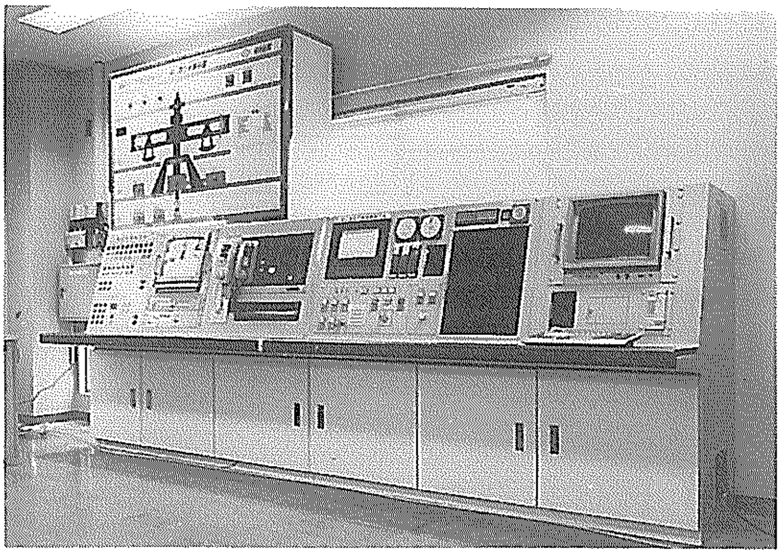


Fig. 22 Operation desk and control panel

3.4 Ancillary equipment

(1) Electric slip rings and rotary joints

Various accessory tools and equipment are available to conduct experiments in a high *g* field levels. They include loading devices for bearing capacity study, sand hopper for embankment construction, vane tester and cone penetrometer for measuring in-situ strength of the model ground during the flight. In order to drive these equipments during the flight, electrical slip rings were installed at the bottom part of main shaft to supply 3-phase electricity of 200 V to the centrifuge. **Figure 23** shows the position of electrical slip rings and rotary joints. The electricity is transformed to 3-phases of 200 V, 2-phases of 100 V and DC 24 V, and each electric phase can be controlled individually by means of the switching circuit shown in **Fig. 24**. Hydraulic, water and air pressures are also supplied to the platform through the rotary hydraulic joints installed at the bottom part of the shaft.

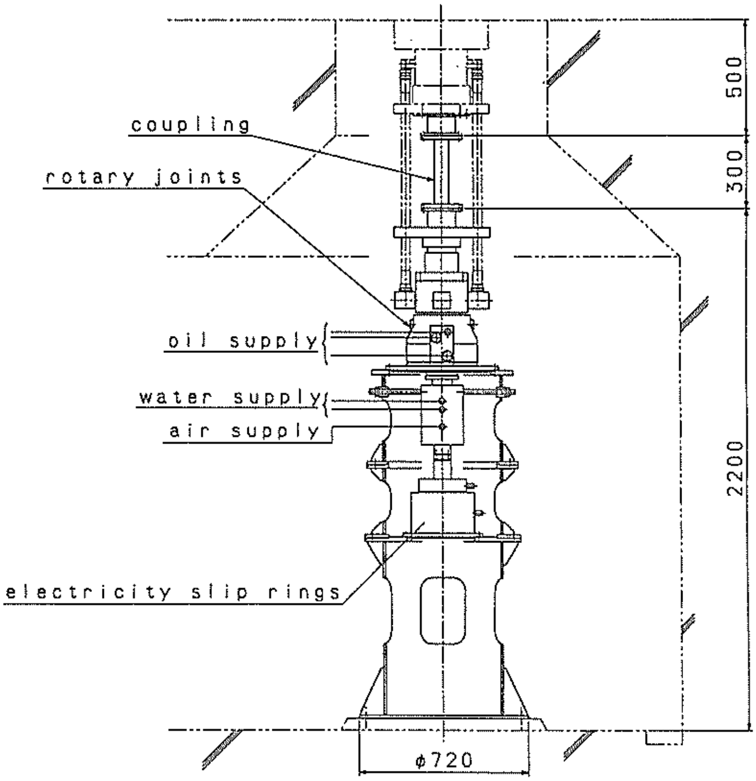


Fig. 23 Electric slip rings and rotary joints

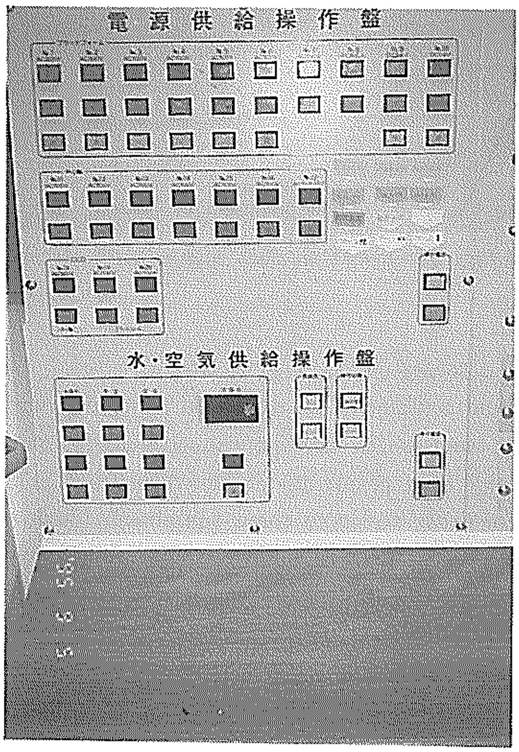


Fig. 24 Switching circuit

(2) data acquisition systems

Figure 25 shows the data acquisition system and photo acquisition system installed in the Mark II centrifuge. There are two data acquisition systems installed in the Mark II centrifuge for static and dynamic measurements as shown in **Fig. 26**. For the static measurements electric signals received by various transducers are transmitted through a slip ring stack of 44 poles on the top of main shaft from the swinging platform to the operation room. The analog signals from the transducers are measured and converted to the digital signals in a strain meter, inputted to a personal computer, stored in a floppy disk and displayed on a CRT after performing certain computations. For the dynamic measurements the electric signals are converted to the digital signals in a A/D convertor on the centrifuge (**Fig. 14**) and then it is transmitted through a fiber optical rotary joints to the operation room. The A/D convertor and amplifiers are simultaneously controlled through the GP-IB system from the operation room. The signals to control the switching circuit for electricity supply are also transmitted through the slip rings from the operation room to the centrifuge.

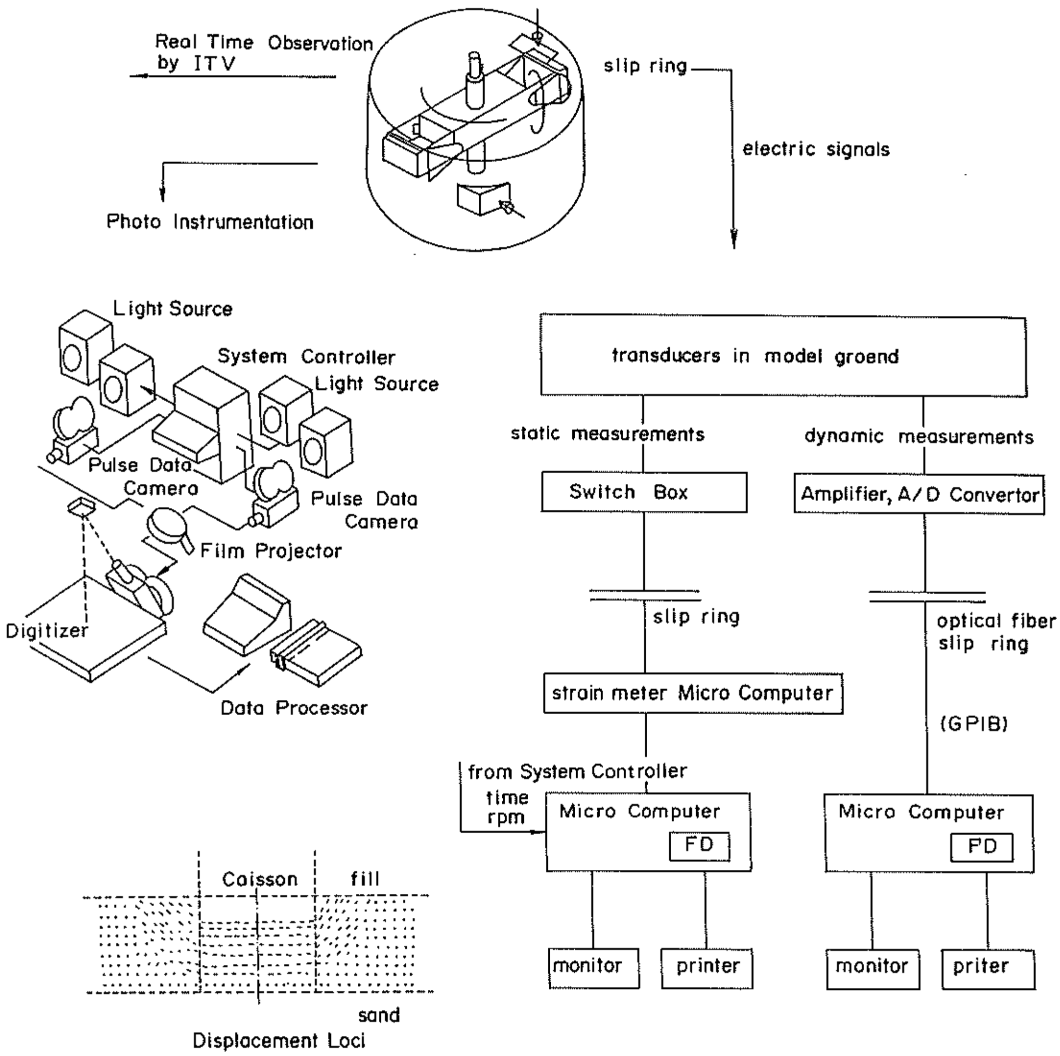


Fig. 25 Data acquisition systems

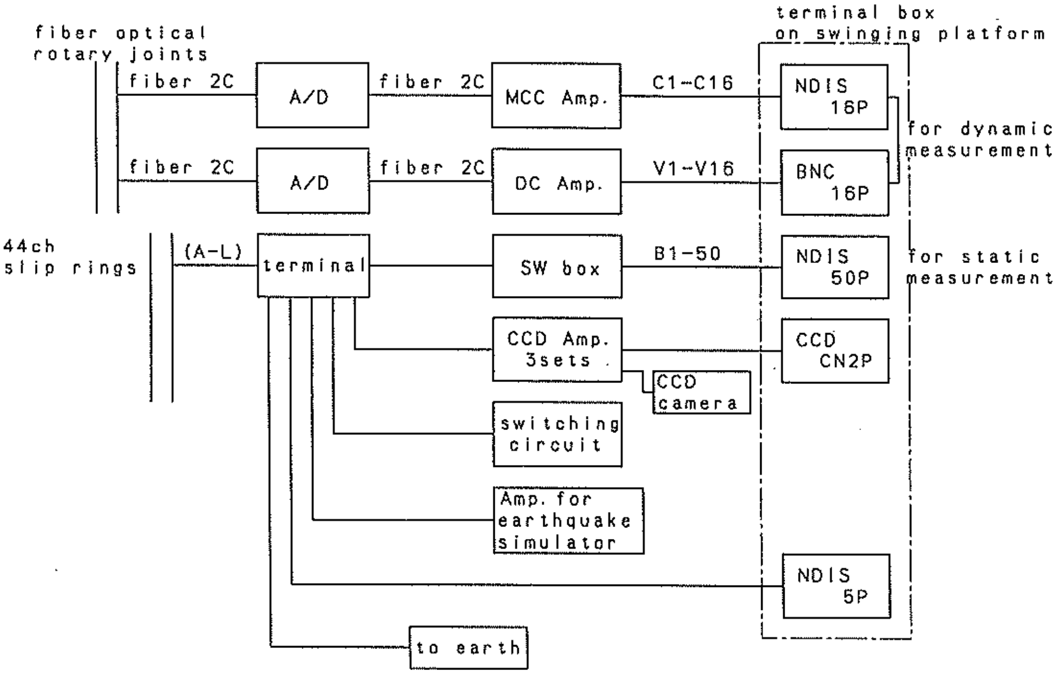


Fig. 26 Data acquisition system

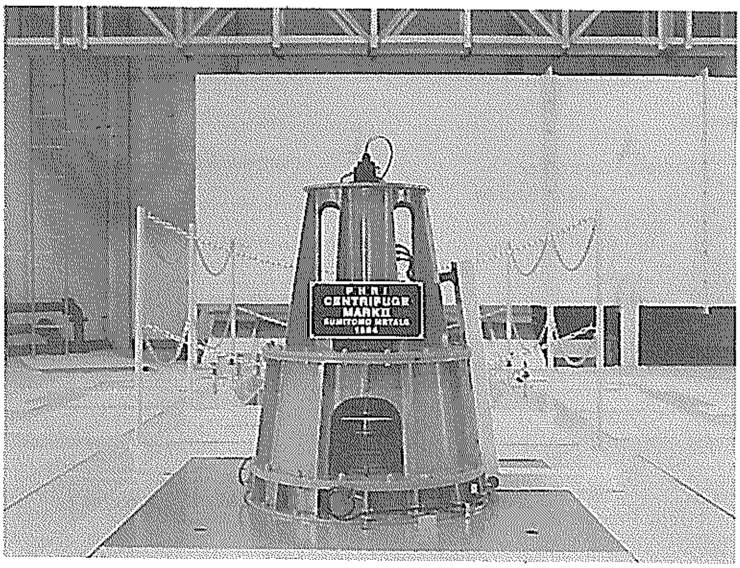


Fig. 27 Slip rings

(3) Photo acquisition system

Photograph of the model ground in the specimen box can be taken from two different angles in the pit; one is through the opening in the side wall of the concrete pit (the shooting window I) and the second is through the opening in the upper floor of the pit (the shooting window II), as shown in **Fig. 28**. Two sets of photographic equipment systems are installed at these two shooting windows. **Figure 29** shows the 70 mm pulse data-camera installed at the shooting window I. The coordinates of target markers on the cross section of a model, taken during the

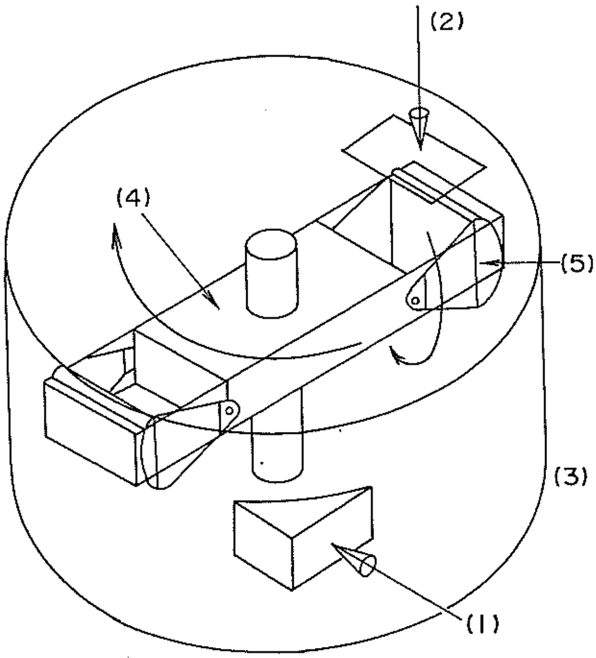


Fig. 28 Schematic view of the centrifuge

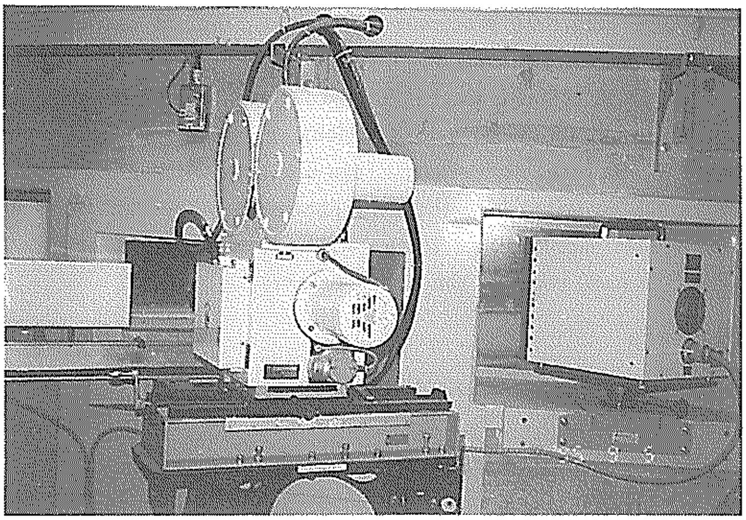


Fig. 29 70 mm pulse-data camera at the shooting window I

flight, are digitized on a large screen digitizer (see **Fig. 30**) and are converted to real coordinates, after making compensation for various sources of distortion using fiducial points on the specimen box. These systems were originally developed for the Mark I centrifuge and all the optical devices of the system were custom designed[2),3),84)] to increase the quality of the photographic images.

A T.V. monitoring system (see **Fig. 31**) is also installed to supplement the photographic system at the shooting window I, which is quite powerful in real time monitoring and quick playback although the quality of the images is not as good as the still photographs. The light source for the still photograph is the same as the one used for the T.V. camera.

Fig. 30 Projector, digitizer and data processor

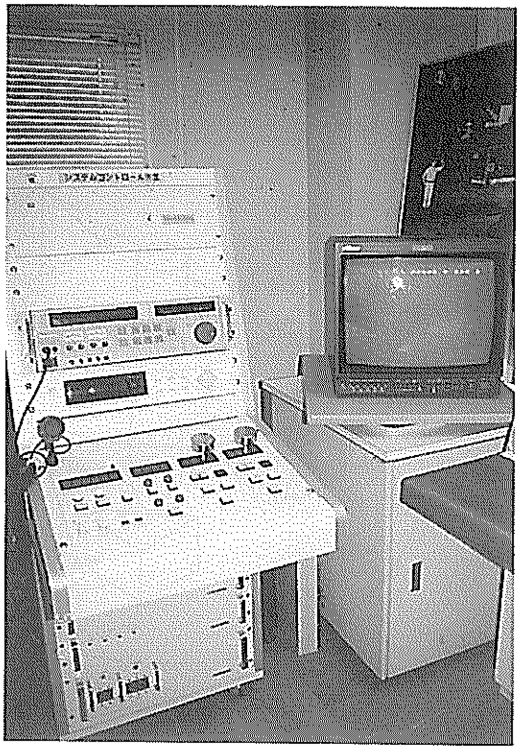


Fig. 31 Photo system

The video system incorporates three CCD (Charged Couple Device) cameras on the centrifuge to monitor the model ground from various directions and also recorded the experiment. The photographic signals are amplified on the centrifuge and transmitted through the slip rings to the operation room, which contributes to the clear photo images without any noise through the line. A color printer is also supplemented to the system which can capture the T.V. images at any time and provide the hard copy of the model behavior.

4. Concluding Remarks

This paper describes the summary of operation of the Mark I centrifuge and the development of the Mark II centrifuge facilities.

Since the construction of the Mark I centrifuge in 1980, it had been employed extensively to investigate not only on basic research topics but also on practical topics with close relation to specific prototype. The results of these research projects have been applied and reflected to the constructions of various port and harbor facilities, which has proved the importance and effectiveness of the centrifuge model testing.

The new centrifuge, Mark II, has the same dimensions and capacity as the Mark I, however, the control systems and safety systems have enormously improved to accommodate the 14 years' operation and experiences into the new facilities. And also the data acquisition system was totally replaced by advanced systems for the Mark II centrifuge. The Mark II centrifuge is believed to be one of the most effective and functional centrifuges in the world.

PHRI belongs to the Ministry of Transport which is responsible for the design and construction of port and airport facilities. Great demands exist to simulate not only ideal prototype-scale structures but also the site specific prototypes. The challenging but fairly difficult field of centrifuge application will be one of the major subjects of the PHRI Mark II centrifuge in the near future.

(Received on September 28, 1995)

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港湾技研資料 No.817

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編集兼発行人　運輸省港湾技術研究所

発　行　所　運輸省港湾技術研究所
横須賀市長瀬３丁目１番１号

印　刷　所　㈲つばさ印刷技研

Published by the Port and Harbour Research Institute.
Nagase, Yokosuka, Japan.