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APPLICATION OF HIGH DAMPING MATERIAL TO FOUNDATION WORK FOR REDUCTION OF EARTHQUAKE RESPONSE

K. Miura[1], M. Hirota[2], K. Ishimura[2], Y. Kiyota[1], Y. Suzuki[1] and M. Nagano[1]

[1]Kobori Research Complex Inc., Tokyo, Japan
[2]Tokyo Electric Power Company, Tokyo, Japan

ABSTRACT

This paper describes a foundation work for reducing the earthquake response of structures founded on firm rock. A high damping material is laid in the clearance between the basemat and the underlying rock, thus giving a higher damping factor to the structure and reducing its earthquake response. The applicability of the high damping material to the foundation work is discussed.

1.INTRODUCTION

Nuclear power plant facilities in Japan have been and will continue to be founded on firm rock. As these facilities are rigid and massive, their dynamic behavior is strongly affected by dynamic soil-structure interaction(SSI). The damping factor attributable to SSI is almost proportional to the non-dimensional frequency $a_o = \omega b/Vs$(ω:circular frequency,b:width of foundation,Vs:shear wave velocity of underlying rock). As Vs increases with rock firmness, larger damping factors can not be anticipated for these facilities and larger earthquake response must be inevitably taken into account.

The foundation work described herein comprises laying a high damping material(HDM) in the clearance between the basemat and the underlying rock, thus giving a higher damping factor to the structure and reducing its earthquake response. This foundation work is hereafter termed FWRE. A previous paper[1)] proposed FWRE and presented frequency response analysis results to examine its effectiveness. A mixture of gravel and asphalt was chosen for the HDM and the material test results on this HDM were also described.

This paper presents results of research which progressed onto the examination of the applicability of the HDM to FWRE.

2.FOUNDATION WORK

The foundation work is assumed to be applied to a nuclear reactor building of the FBR (Fast Breeder Reactor) type, constructed directly on an outcrop of firm rock whose shear wave velocity Vs=2000m/sec., unit weight γ_t=2.3t/m^3, and Poisson's ratio υ=0.4, and which provides 1% hysteresis type damping. The building will be 63m high from the bottom to the roof and it will weigh 200,000tons. The basemat will be 63mx65.5m in plan and 5m thick. The ordinary average vertical pressure σ_v underneath the basemat due to the weight of the building amounts to about 5kg/cm^2.

If the building is constructed by conventional methods(CCM), the basemat will be buried in rock with a 3m side clearance. After completing the basemat construction, this clearance will be filled with man-made rock(MMR). For the FWRE, the rock underneath the basemat will be excavated by D meters, and this excavation and the side clearance will be paved with the HDM. Fig.1 illustrates the buildings in which the CCM and the FWRE will be adopted.

3.EARTHQUAKE RESPONSE

Earthquake response analyses were performed to examine the effectiveness of the FWRE. The axi-symmetric finite element method was employed for the analysis: the same as in previous paper. The building was represented by a lumped mass system with 5% hysteresis type damping, as shown in Fig.1. The material constants of the MMR in the CCM were set at Vs=1920m/sec., γ_t=2.4t/m^3, υ=0.167 and h=0%. Based on the material test results, the material constants for HDM were Vs=400m/sec., γ_t=2.2t/m^3, υ=0.3. The damping factor h_m and the thickness D of the HDM were selected for analysis parameters. Fig.2 and Fig.3 show the acceleration time history and acceleration response spectrum of the input earthquake motion imparted at the rock surface. This earthquake input motion corresponded closely to the maximum design earthquake(S1) in Japan.

The eigenvalue analyses indicate that the first natural frequency of the building is 5.1Hz for the CCM and 4.1Hz for the FWRE with D=5m. Earthquake response analyses were performed for various values of D and h_m, and the standard deviation of response accelerations are shown in Fig.4. Fig.5 shows the acceleration response spectra for the CCM and the FWRE (h_m=15%,D=5m) at three mass points of the building indicated in Fig.1. Mass No.1 is on the roof, No.4 on the refueling floor and No.10 in the basemat. The followings are determined from these results.

(1)The response accelerations decrease with increasing thickness D of the HDM and are almost stabilized at D=5m. Further effectiveness of the FWRE can not be anticipated with a greater thickness, D.

(2)The effectiveness of the FWRE is distinct when the h_m of the HDM exceeds 15%.

(3)The FWRE is more effective in reducing the earthquake response at the upper floors of the building than at the lower floors.

Fig.6 depicts the maximum shear strain in the HDM. The maximum shear strains are distributed between 0.02 and 0.05% in the HDM underneath the basemat.

4.MATERIAL TESTS

4.1 Apparatus and Specimens

A mixture of gravel and asphalt, termed Asphalt Gravel(AG), was chosen for the HDM. Cost, durability and workability were taken into account in making this chose. The specifications of the gravel employed in the test were; specific gravity Gs of particle :2.73, mean grain size D_{50} :3.2mm and uniformity coefficient Uc: 26.0. The asphalt was a straight asphalt whose specifications were; penetration at 25°C: 69, softening point: 47.5°C and specific gravity: 1.026. After warming the asphalt until it became fluid, it was poured onto the gravel to produce the AG. Test specimens were produced by putting this AG into a mold and compacting it with a vibrator. The asphalt content was decided so as to obtain the most suitable content ratio determined by the Marshal stability test for asphalt pavement work. Zero permeability was confirmed by the permeability test on the AG in accordance with the Marshal test results.

The dynamic loading test apparatus shown in Fig.7 was employed. This apparatus performed much better than that used in the previous study, in actualizing the earthquake events, and it could apply dynamic loads in both the horizontal and vertical directions while maintaining the initial vertical static load. Both an earthquake wave and a sine type dynamic loading were actualized by this apparatus. The test specimens were rectangular planks 80cm square and 30cm high. To avoid stress concentration at the corners of the specimen, four corners were cut off. Nine specimens were prepared and tested under the conditions tabulated in Table 1. The temperature of the specimen could not be controlled, so it depended on room temperature during the tests.

4.2 Dynamic Deformation Tests and Results

Dynamic deformation tests were performed by applying horizontally the sine loading of 1 Hz to the specimens under the five vertical stress conditions indicated in Table 1. Fig.8 shows the test results for the relations between shear modulus G, damping factor h_m and shear strain γ. The vertical axis indicates the normalized shear modulus G/Go in which Go is the shear modulus at the smallest shear strain. As the strain increases, the shear modulus decreases gradually and the damping factor increases. The damping factors are more than 15% even if the strains are very small and the vertical stresses conditions are changed. The effects of the vertical stress on the shear modulus and the damping factor at two strain levels are indicated in Fig.9. As the vertical stress increases, the shear modulus increases and the damping factor decreases slightly.

The influence of excitation frequency on the shear modulus and the damping factor is shown in Fig.10. As the excitation frequency increases, the shear modulus increases and the damping factor decreases slightly.

Fig.11 shows the calculation results for the shear and vertical stress time histories in the HDM near the edge of the basemat. The horizontal force corresponding to the shear stress time history shown in Fig.11 was applied to the specimen. This force was amplified 4, 6, and 8 times, and also applied one after another. These four horizontal forces were applied with the vertical pressure at 5 kg/cm^2 and the temperature between 17.5°C and 18.5°C.

A half hysteresis loop was set as the stress-strain path between adjacent zero crossing times when the stress was just zero, and the relations between the shear modulus, the damping factor and the shear strain were evaluated from the half hysteresis loop. These parameters were evaluated for the duration of the force application. Fig.12 plots together the evaluated parameter values for the four forces. As with the sine excitation shown in Fig.8, the shear modulus decreases and the damping factor increases as the strain increases. Because the results shown in Fig.12 are those under the earthquake wave type excitation, the damping factors are scattered. However, it can be concluded that the AG provides a damping factor of more than 15% even under the earthquake excitation.

Fig.13 shows the stress-strain paths when the horizontal and vertical forces shown in Fig.11 were applied simultaneously. The loops for shear stress τ and strain γ indicate a higher damping factor. The loop for vertical stress σ and strain ε gets slightly out of the usual loop shape. This loop occurs because the rigidity increases with increasing vertical stress, and conversely it decreases with decreasing the vertical stress.

Under various vertical stresses, the shearing strengths of the AG were examined, as shown in Fig.14. As the vertical stress increases, the strength increases, as for a normal sand. After the AG reaches its maximum strength and is subject to larger strain, the bearing capacity does not decline rapidly and a higher ductility feature can be recognized. It can be judged that the AG is strong enough and is suitable for the paving material underneath the basemat of the building.

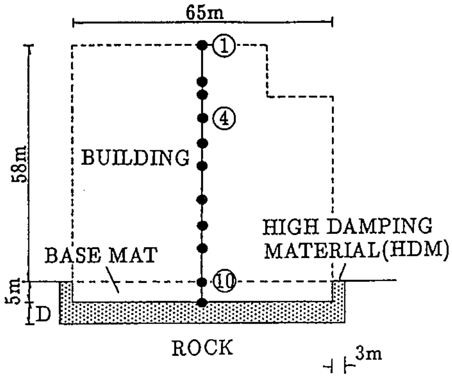
The AG must be mainly durable against water and ultraviolet rays. No water permeated through the AG specimen, as described before. The AG will be paved underneath the basemat and never exposed to sunlight. Thus, it must be durable.

5. CONCLUSIONS

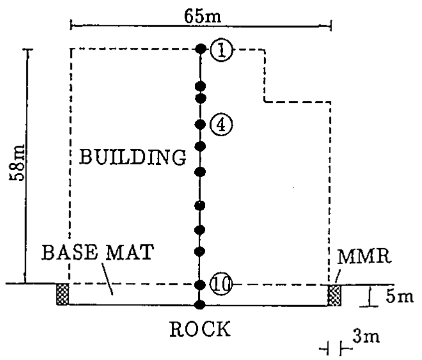
The applicability of a high damping material was examined for application to the foundation work for reducing the earthquake response of a building constructed on firm rock. A mixture of gravel and asphalt(AG) was chosen for the high damping material and analytical examinations and the element tests were carried out. As results of this investigation, it can be concluded that the AG is applicable to this foundation work.

REFERENCE

1)Miura,K.,et al. 1992. Foundation work for reduction of earthquake response, Proc. of Tenth World Conference on Earthquake Engineering, Vol.III,2251-2256

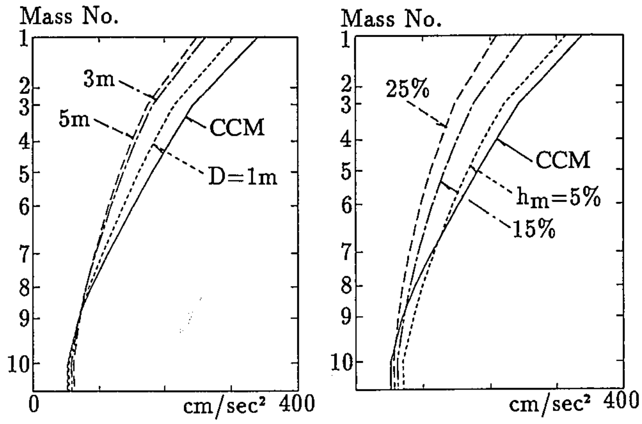


(a) Foundation work for reduction of earthquake response (FWRE)



(b) Conventional construction method (CCM)

Fig.1 Foundation Works



(a) h_m=15% (b) D=5m

Fig.4 Distribution of standard deviation of response accelerations

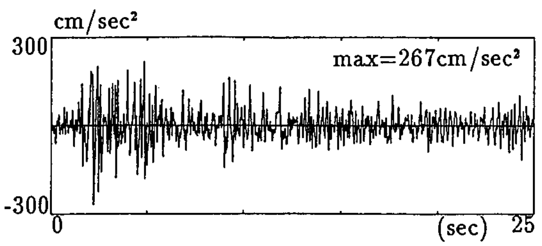


Fig.2 Acceleration of input earthquake motion

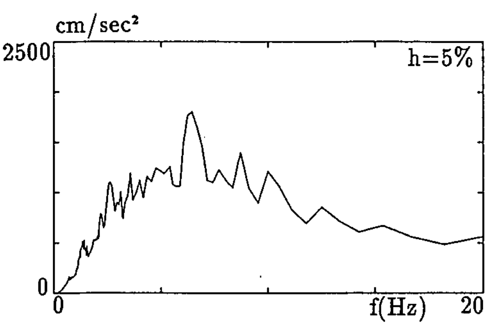


Fig.3 Acceleration response spectrum of input earthquake motion

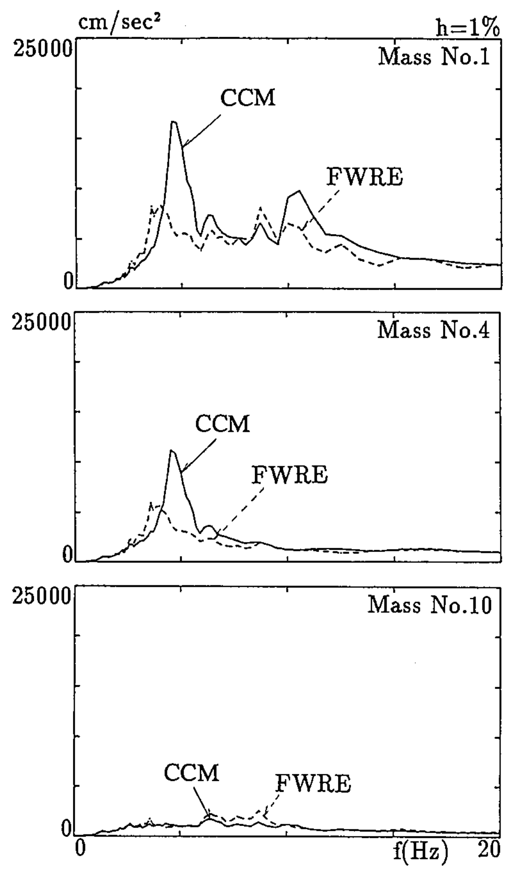


Fig.5 Acceleration response spectra of building (h_m=15%,D=5m)

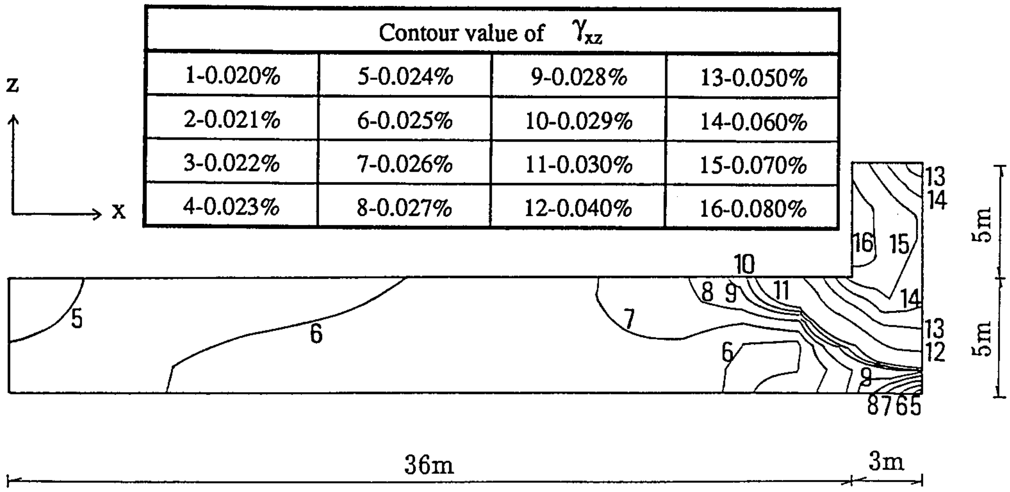


Fig.6 Maximum shear strain in HDM layer

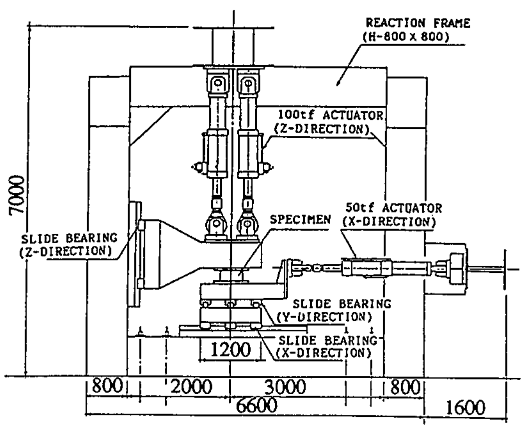


Fig.7 Test Apparatus

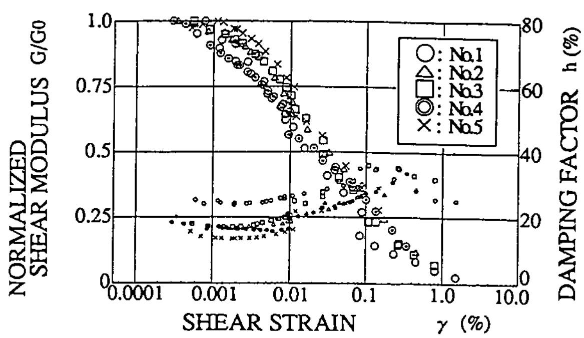


Fig.8 Shear modulus and damping vs. shear strain for specimens

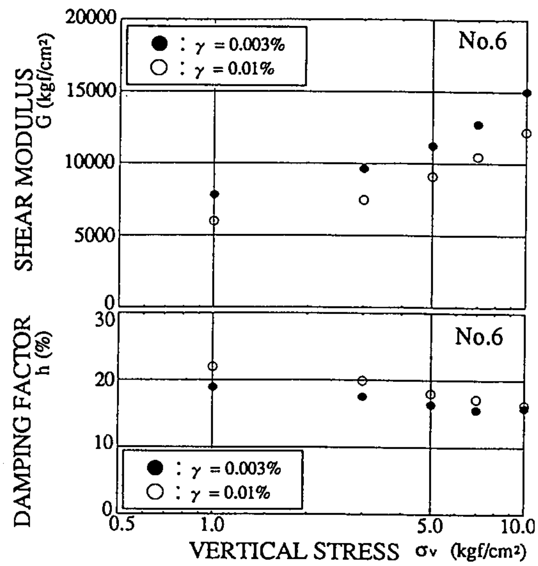


Fig.9 Shear modulus and damping vs. vertical stress

Table 1 Test conditions

Test No.	Test type	γ_t (gf/cm³)	σ_v (kgf/cm²)	f (Hz)	T (℃)	G_0 (kgf/cm²)
No.1	γ test	2.312	1.0	1.0	21.0~23.5	6656
No.2	γ test	2.308	3.0	1.0	14.5~17.0	14540
No.3	γ test	2.378	5.0	1.0	20.0~21.0	10280
No.4	γ test	2.317	7.0	1.0	18.5~19.0	17320
No.5	γ test	2.316	10.0	1.0	18.0~19.0	17200
No.6	σ test	2.316	1.0~10.0	1.0	19.0~19.5	—
No.7	f test	2.393	5.0	0.01~10.0	18.5~19.5	—
No.8	E1 test	2.343	5.0	—	17.5~18.5	13030
No.9	E2 test	2.342	5.0	—	18.0~19.0	11490

γ test : Dynamic deformation test for various shear strains,γ
σ test : Dynamic deformation test for various vertical stresses,σv
f test : Dynamic deformation test for various frequencies,f
E1 test : Horizontal earthquake excitation test
E2 test : Horizontal and vertical earthquake excitation test
γt : Unit weight, f : Frequency
T : Temperature, σv : Vertical stress, G0 : Initial shear modulus

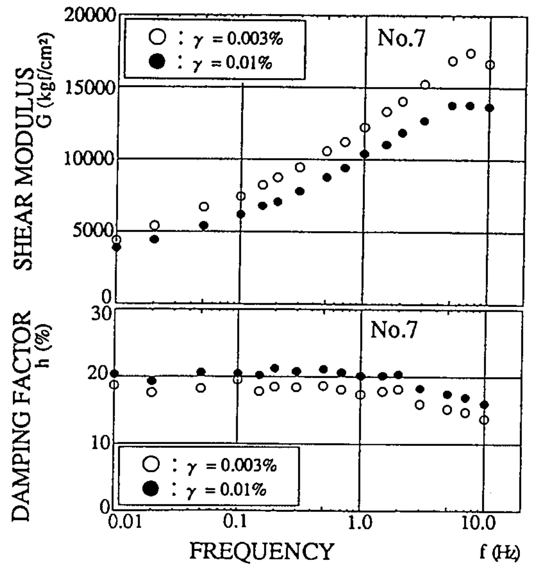


Fig.10 Shear modulus and damping vs. frequency

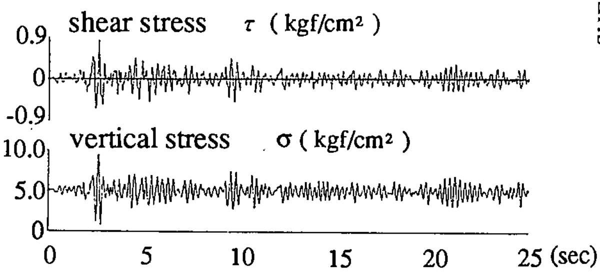


Fig.11 Response time histories for horizontal and vertical input waves

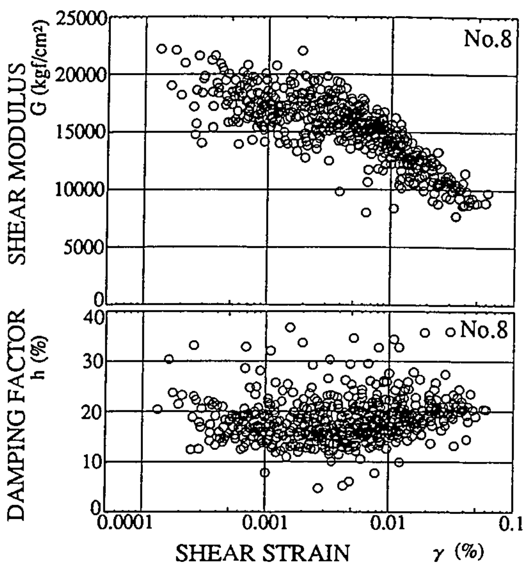


Fig.12 Shear modulus and damping vs. shear strain at earthquake response

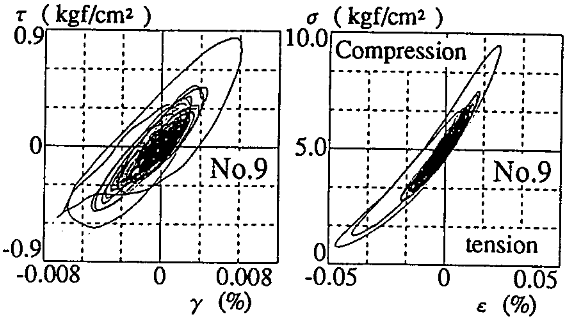


Fig.13 Hysteresis loops for horizontal and vertical input waves

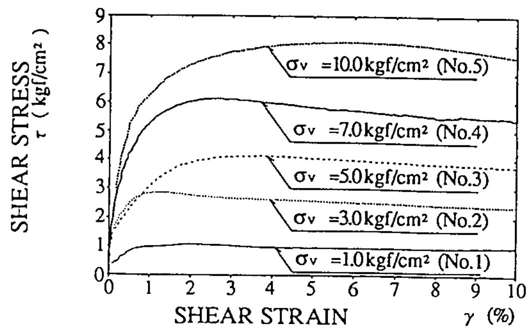


Fig.14 Shear stress-strain curves for various vertical stresses