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STRENGTH OF REINFORCED CONCRETE SLAB WITH SAND CUSHION AGAINST FALLING WEIGHT IMPACT AND A DYNAMIC DESIGN METHOD OF ROCK-SHELTER

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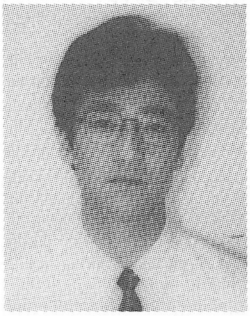
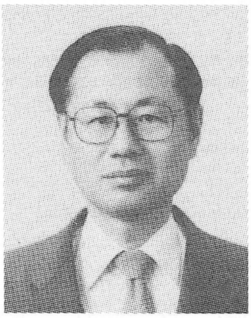

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SYNOPSIS

Although many reinforced concrete rock shelters have been designed against static loads that are of same level as the maximum rock impact, the design should be carried out by dynamic analyses.
In order to grasp shelter slab's behavior under falling rock impact, we executed dynamic and static loading experiments on RC slabs with sand cushion. It was found from the results that impact force brings far less displacement or strain to RC slab than that of static loading case. Time-lag between impact force and slab's response explains most part of such difference. The results of these experiments were ascertained by F.E.M analyses, and at the same time, a dynamic design method for rock shelter was presented.

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1. INTRODUCTION

Designs for shelters protecting against falling rock loads currently use static loads of the same intensity as the maximum impact force on the top slab. However, at the collision of the falling rocks, the impact force transmits to the structure in a moment, and here the behavior of the structure differs from a static loaded condition. To design rock-shelters to withstand falling rock loads, "it is necessary to evaluate the ultimate resistance of the structure against impact forces and to understand the energy absorbed by the elastic and plastic deformation of the structure," (Falling Rock Protection Manual, Japan Road Association 1983), although no generally accepted dynamic design method to use with falling rock loads has been presented because there are several difficulties in generalizing rock-shelter behavior at falling rock collisions: impact forces of falling rocks may act at randomly in terms of magnitude, changes with time, and area distribution; it is necessary to know how the rock-shelter responds to the impact (Designing becomes even more complex when there might be a close interaction between impact force and response).

Studies of the design of rock-shelters have so far focused only on a formulization of impact forces due to falling rocks. These works have achieved some measure of success.[1)-4)]

It has been suggested that the strength of reinforced concrete slabs provided with sand cushions against falling rock loads is higher than that against static loads[5)] though it has not been shown quantitatively. This study investigates the behavior and strength of top slabs of RC rock-shelters under the impact of falling rocks, and presents a rational design method for rock-shelters.

The study employs impact experiments with RC slab models and numerical analysis. The experiments provide the properties of falling rock loads and the ultimate strength of RC slabs. The numerical analysis leads to a dynamic design for rock-shelters. These two approaches cooperate to enable the establishment of a dynamic/ultimate design method for rock-shelters subjected to falling rock impacts.

2. OUTLINE OF EXPERIMENTS

Loading experiments were carried out on top slabs as most rock-shelters are gate or rectangular rigid frame types where the falling rock loads on the top slabs are dominant in determining section designs of the shelter. Considering the existing design method in which the structure is represented as a two-dimensional rigid frame, the RC test slabs are supported on two sides with hinges to minimize measurement errors. They were loaded dynamically and statically.

In the impact loading where experiments were performed by dropping a weight to the sand cushion on the RC slab (Figure-1), measurements were made on negative accelerations of the weights at collision, strains of the main steel bars, and accelerations and displacements of test slabs. In some experiments, earth pressure gauges were installed on the surface of the RC slab to observe the impact force transformation into soil pressure.
The upper limits of response frequencies in the measuring instruments are 2kHz in the accelerators, 400Hz or more in the earth pressure gauges, 1kHz in the inductance displacement gauge, and 60kHz in the strain gauge. The data was recorded on a personal computer at sampling times of 0.2msec. The response frequencies of the measuring instruments are sufficiently high for the accuracy of measurements.

Shape of the weights, falling height, and thickness of sand cushion were so determined that the collision in the experiments would approximate to actual phenomena; The weight shape and the cushion thickness were so determined that the dispersion center of the Calculated Lamé Values, an indicator of impact magnitude, would be within the range of 100-400tf/m^2 which is estimated in ordinary designs.

Static loading experiments were performed for the comparison with the impact loading experiment, where the load was applied through the weight to the sand cushion to ensure that the load distribution would be close to that under impact.

The sand cushion material was fine concrete aggregate compacted by stamping. The degree of compaction was tested with a Dutch cone penetrator.

The standard design strength of the slab concrete (Figure-2) was 210kgf/cm^2. The elastic coefficient obtained from breaking tests on test pieces was 1.73 × 10^5 kgf/cm^2 in average. The steel bars used here were SD30 D10.

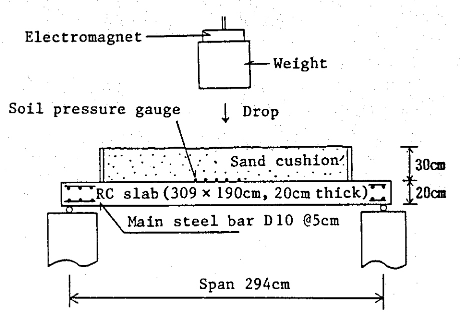


Fig.1 Plan of Impact Loading Experiment.

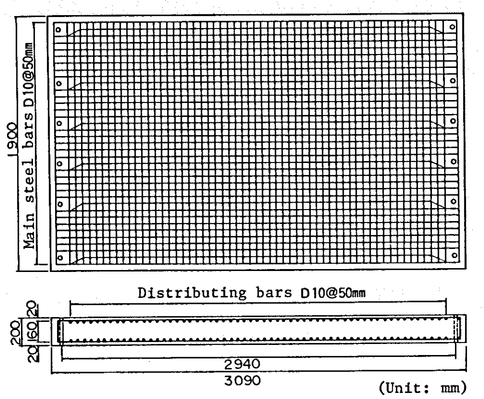


Fig.2 Test RC Slab.

3. RESULTS OF EXPERIMENTS

3.1 Behavior at Collision

From falling weight experiments on 7 RC slabs, 16 sets of data were obtained as shown in Table-1. White rows show the strength of intact RC slabs against impact, the result of the first falling weight test. Tests No.1-2 and 3-2 which are, in fact, the results of second tests, are categorized into the white rows as the weight levels in the previous 1-1 and 3-1 tests were not high enough to change the properties of the slabs.

Data in black rows show changes in strength for one RC slab with repeated impacts of falling weights.

Figure-3 shows the relation between weight acceleration and soil pressure on the slab in Test 1-1. The first peak of the negative weight acceleration may probably be the result of the initial resistance of the sand cushion to the penetration of the weight. Because of the thinner sand cushions here, the soil pressure responded vis-à-vis to the acceleration of the weight not as in the other tests.[2)-4)] The distribution of the soil pressure at the first peak is

Table 1 Results of Impact Loading Experiments.

Test No	Weight (kgf)	Falling Hight (cm)	Cone Test qc of SandCushion (kgf/cm²)	Negative Accelaration of Weight (-G max)	Impact force (tf)	Calculated Lamé Value λ (tf/m²)	Displacement of slab at centre (mm)	Strain of steel ber (μ) at slab centre	Strain of steel ber (μ) 10cm apart from centre	Strain Rate **** (%/s)	Behaviour of Weight Accelaration: First peak Time T₁ (sec)	Behaviour of Weight Accelaration: Ending time T₂ (sec)	Behaviour of Weight Accelaration: Accelaration
1-1	300	60	2.50	16.9	5.1	100	1.1	330	270	1.8	0.013	0.057	
1-2	600	300	3.28	39.3	23.6	129	6.4	1760	1660	10.3	0.010	0.060	
2	800	300	3.36	33.6	26.9	111	9.3	2730	2640	15.6	0.009	0.064	
3-1	1000	60	2.67	8.3	8.3	45	4.5	915	790	2.4	0.016	0.097	
3-2	1000	180	3.10	14.3	14.3	34	7.1	1940	1770	5.0	0.013	0.075	
4	1000	300	3.11	39.4	39.4	199	11.5	2320	2855	17.3	0.008	0.069	
* 5	1000	200	6.69	65.7	65.7	1310	18.3	3145	3890	29.6	0.005	0.058	
6-1	1000	300	5.85	50.9	50.9	377	12.7	2630	2340	25.1	0.004	0.066	
** 6-2	〃	〃	not observed	21.9	*** 21.9	46	13.2	18000 以上	2422	—	0.014	0.076	
** 6-3	〃	〃	〃	21.7	*** 21.7	45	13.6	2804	2359	—	0.012	0.076	
6-4	〃	〃	〃	86.9	86.9	1435	14.9	1775	2484	—	0.003	0.059	
6-5	〃	〃	〃	89.4	89.4	1540	15.2	1450	2508	—	0.005	0.069	
* 7-1	1000	300	3.71	84.6	84.6	1342	14.4	10000 以上	3140	44.9	0.004	0.060	
* 7-2	〃	300	4.45	125.7	125.7	3610	16.2	3420	10000 以上	—	0.004	0.063	
* 7-3	〃	300	3.60	26.7	26.7	75	14.7	2150	1570	—	0.009	0.065	
* 7-4	〃	240	3.60	440	44.0	366	14.0	1770	1355	—	0.007	0.065	

* Sand cushion thickness 20cm. 30cm for others
** weight not dropped straight
*** at second peak
**** Strain Rates are calculated only for the initial state of the slab.

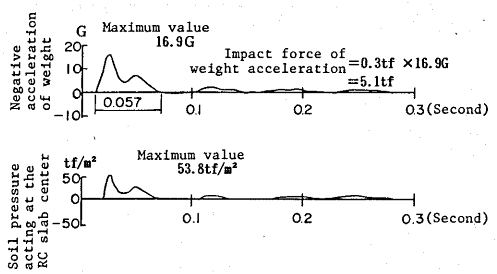


Fig.3 Correspondence of Weight Acceleration with Soil Pressure on RC Slab.(Test No.1-1, Weight 300kgf, Drop height 60cm)

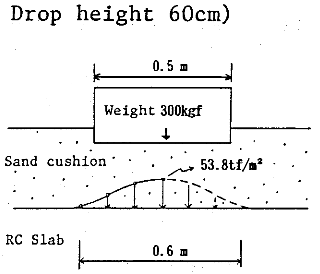


Fig.4 Distribution of Impact Force on RC Slab through Sand Cushion.

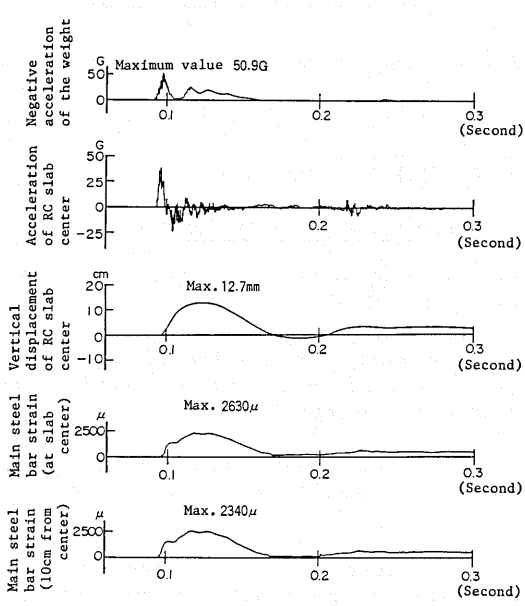


Fig.5 Behavior at Falling Weight Impact. (Test No.6-1, Weight 1,000kgf, Drop height 300cm)

shown in Figure-4. The sum of soil pressures, which is calculated by assuming the whole distribution form of the observed values, is nearly equal to the product of the mass and acceleration of the weight.

Figure-5 shows the behavior of the RC slab and weight in Test No.6-1. It is noticeable that both the maximum response of the vertical slab displacements and the main steel bar strain apparently lag behind the first peak in the weight acceleration.

The slab gives so limited main response when the weight reaches the maximum acceleration that there indicated no dynamic interaction between the weight and the slab; The behavior of the weight is influenced only by the sand cushion. Regarding the sand cushion and the slab as springs of very different rigidities, above mentioned behavior would be explained by the fact that the energy of an object colliding with a compound spring of very different rigidities is almost all absorbed by the weaker spring.

There may occur an anxiety that a decrease in the rigidity of the slab due to response yield causes interaction between slab and load, but this would not happen as the load itself would already have decreased at this moment.

3.2 Calculated Lamé Values and Rising Up Time of Impact Force

The Calculated Lamé Values λ in Table-1 were obtained by substituting the test results into $P = 2.455W^{2/3} \cdot \lambda^{2/5} \cdot H^{3/5}$, the formula of falling rock impact force, shown in The Vibration Manual, Japan Society of Civil Engineering.

As Lamé Value λ in the above formula represents the softness of the cushion material, a close relationship between Lamé Value and the rising up time of the weight acceleration is expected. The plotting of the experiment results shows that they are well and inversely correlated (Figure-6).

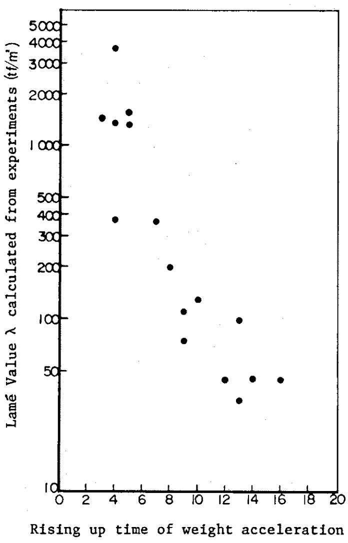


Fig. 6 Relation between Rising Up Time of Weight Acceleration and Calculated Lamé Value.

Lamé Values in rock-shelter designs generally are of 100-400tf/m^2. The experimental results with Calculated Lamé Values in this range give the average continuance of the weight acceleration of 0.0635 seconds and the average time to reach the maximum value from the start of 0.0085 seconds. Then it is recommended that the wave of the impact force for dynamic designs of rock-shelters described later forms an isosceles triangle with a base of 0.0170 seconds for the first peak.

3.3 Initial Strength of RC Slab against Impact

Plotting the impact loading test results shown in Table-1 and the static loading tests results, Figure-7 shows the load-strain relationships of the main steel bars. In the same way, Figure-8 shows load-displacement relationships of slabs. The plotted lines of the impact and static tests are in agreement at the lower loading stages, but the lines are widely apart at the higher loading stages. That is, at the static loading tests the rigidity of the RC slab decreases due to cracks after 11tf load, and it apparently yields to 22tf load while the RC slab under the impact test shows elastic behavior below 65.7tf though there is a dispersion of values due to differences in load waves.

The first explanation of the difference stated above is the time length and speed of the loadings. Under the conditions of rapid and instantaneous loading, load and response do not behave in tandem. In Figure-5, there is no agreement in wave form and peak time for the negative acceleration of weight (≈load) and the slab displacement (or the steel bar strain). The natural period of the RC slab is calculated to be 46.9m/sec, considerably long compared with the cycle of load waves. The a lack of coincidence in responses naturally followed. Thus slab behavior was strongly influenced by the primary mode of vibration, and the maximum response occurred after the end of the first load crest. Put simply, an RC slab with an initial velocity given by the impact force would produce the primary vibration. In spite of the yield of steel bars and a decrease in the rigidity of slab during the increase in displacement, the force, [the decreasing impact force] + [the inertial force of the slab], did not continue to increase the response.

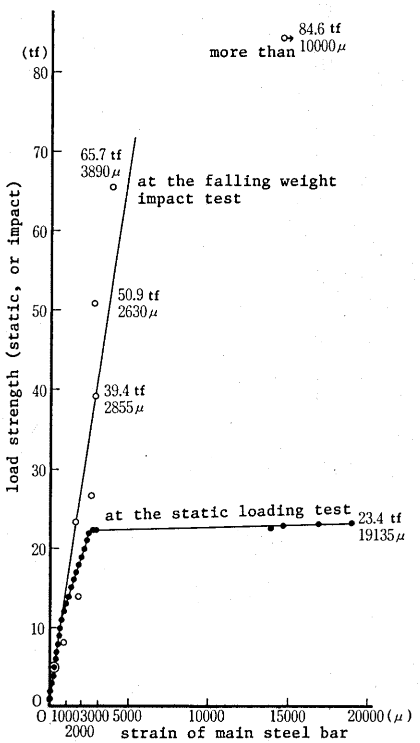


Fig.7 Relation between Load and Main Steel Bar Strain at Impact and Static Loading Tests.

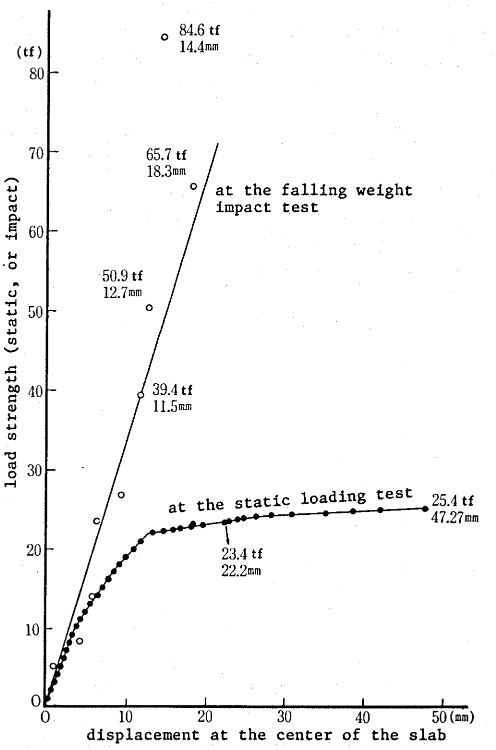


Fig.8 Relation between Load and Vertical Displacement of RC Slab Center at Impact and Static Loading Tests.

The second reason to explain the differences in state between the static load and the falling weight impact tests is the fact that yield points of steel bars and concrete rise up under rapid loading. In dynamic one-directional simple loading experiments of steel bars by Mutsuyoshi et al.[6] it is reported that the upper yield point under 50%/sec strain rate is 27-40% higher than that under 0.05%/sec strain rate. For example, the main steel bar strain in Test No.5 (see Table-1), rose 3,890μ at 0.013sec after the start of strain (strain rate 30%/sec), then after the impact, the bar had a residual strain of 1,100μ. The remainder is 2,790μ. On the other hand, the yield strain of this steel bar at the static load test averages 2,056μ (Table-2). The 734μ difference between 2,790μ and 2,056μ is considered to be an increment of yield point, which is 36% of the static yield strain.

Table 2 Results of Static Tensile Tests of Steel Bars of Test RC Slab. (Steel bar: SD30 D10)

Test piece No.	Yield strain μ	Elastic modulus Kgf /cm²
1	2,033	2.10×10^6
2	2,084	2.10×10^6
3	2,054	2.13×10^6
Average	2,056	2.11×10^6

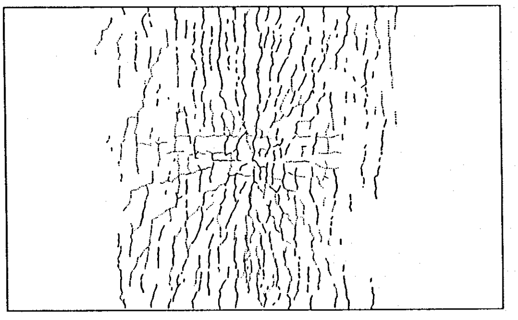


Fig.9 Cracks in RC Slab after Repeated Impact Tests. (Test No.6-1 6-5)
(Solid lines show cracks caused by the first impact. Broken lines are cracks caused by the second and later impacts.)

3.4 Strength of RC Slabs under Repeated Impacts

It would be rare that major rock falls occur twice or more at the very same spot on the top slab of rock-shelters. Nevertheless the possibility should briefly be considered for the length of period in service of civil engineering structures. For that, repeated falling tests were carried out in Tests 6-1 to 7-4.

Figure-9 shows the state of cracks in Tests No.6-1 to 6-5. The test results are summarized as follows:

- In the deformation mode of the slab, "bending" is dominant at the initial impact and at the series of repeated impacts too.
- The primary bending cracks occur at the first impact.
- Repeated impacts generate longitudinal cracks and widen the bending cracks. However, there is no strong increase in the vertical displacement of the slab after several impacts. This suggests that slabs which have been exposed to falling rock impacts maintain their performance against similar loads during the period of service.

4. DYNAMIC DESIGN METHOD OF ROCK SHELTERS AGAINST FALLING ROCK IMPACT FORCES

4.1 Concept

Because that yield stress comes near the breaking stress is a property of structural materials at static loading, a safety factor should be considered for yield stress in the present design system of civil engineering structures. At present, rock-shelters are designed "substituting a static load for the impact force".[1] However, the responses of the structures would be widely different depending on how the load acts; slowly and continuously, or rapidly and instantaneously, even when the loads are of the same level. The behaviors of the RC slab under impact loading tests are summarized as follows:

The start of the slab response lags behind the impact force. The force has decreased before the peak response. In the process of the response, the yield point increases with the strain rate in the main steel bar. The steel bar strain may sometimes surpass the risen yield strain according to the slab displacement. Nevertheless, the slab actually maintains elastic behavior as the force applied has decreased below the yield load. Thus, the behavior under impact loads is different from that under static load in three aspects: loading is not continuous, the load applied to the steel bar at the yield point is low due to the time lag in the response, and the yield point of the steel bar rise up with the high strain rate.

Upon this it may be questioned whether this behavior occurs in an actual structure. To answer this, a theoretical reproduction of the test results is first tried. If the dynamic behavior can be simulated by calculations, same simulation for an actual rock-shelter follows. Then the behavior would be confirmed to actually occur.

Moreover, although the phenomenon of falling rock is highly complicated and irregular, the action of the force is simple once the weight of the falling rock and drop height in a design are set. So, there may be small differences between a theoretical simulation and the actual behavior of the structure. Consequently, some ultimate design considering the dynamic response of the structure becomes possible in designing RC rock shelters subjected to falling rocks.

4.2 Design Method

Such an ultimate design requires ① a maximum impact load, ② a load strength-time curve, ③ a determination of allowable strains (safety factor), and ④ analytical techniques to deal with the impact phenomenon.

① relates to the impact force formula, for which the formula in Falling Rock Protection Manual is suitable. ② is to be obtained by averaging test results. For ③, a slightly awkward item, test results indicate 3,000μ for steel bars.

4.3 Calculations for Test Results

Results from the static and impact loading tests were reproduced by transient dynamic response analysis with the finite element method. "The integrated structural analysis program ISAP" was the tool in the calculations.

The model is an elastic rectangular plate consisting of 600 elements where the RC slab is divided in 20 sections on the short side and into 30 on the long (Figure-10).

All the working was processed in elastic calculations since, as mentioned in 4.1, even when the main steel bar of the slab yields to the impact force, the load at that point has decreased lower than the yield load so that the slab actually behaves like an elastic body. Failure conditions were not set in this calculation.

The distribution of both static and impact force loads were approximated to the test results (Figure-4). The change pattern of the impact force with time was obtained by modeling the waveform of weight acceleration (Figure-10, right), where P_{max} varies for each calculation. The rigidity of the slab model was to be $E = 1.04 \times 10^5$ kgf/cm^2 which was obtained from the load-displacement (at the center of slab) relation in the static loading test (Figure-8). The damping constant was to be $h = 0.05$ calculated from the vibration waveforms of the main steel bar strain in the tests. The mass of the sand cushion was neglected. Calculations were made for Tests No.1-1, 1-2, 3-1, 5, and 6-1. The sampling interval in the calculations was 0.001 second.

Main steel bar strains were obtained by dividing the stress, which was calculated from the bending moment by the elastic coefficient of the steel bar $E = 2.1 \times 10^6 kgf/cm^2$. Calculated results agree well with experimental values as shown in Table-3.

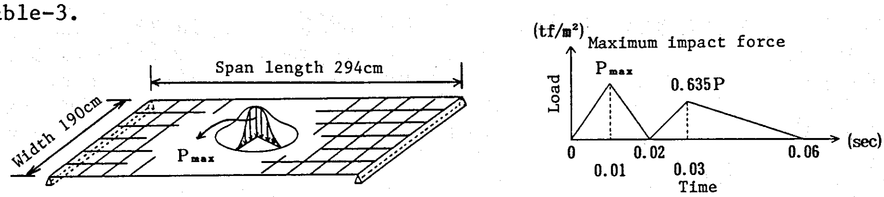
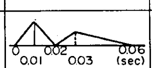
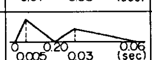
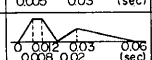
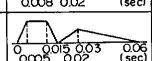
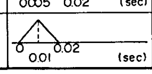


Fig.10 Plan of Dynamic Analysis of RC Slab Behavior at Impact Loading. (Structural system and external force)

Table 3 Comparison of Calculated and Experimented Values.

Calculation					Displacement at slab center (mm)		Main steel bar strain (μ)	
	Test No.	W (kgf)	H (cm)	P (tf)	Experimented	Calculated	Experimented	Calculated
Impact loading	1 − 1	300	60	5.1	1.1	2.6	330	485
	1 − 2	600	300	23.6	6.4	9.4	1760	1659
	3 − 1	1000	60	8.3	4.5	4.4	915	828
	5	1000	200	65.7	18.3	20.2	3890	3804
	6 − 1	1000	300	50.9	12.7	15.0	2630	2989
Static loading		Load 10tf			4.0	3.9	750	786

Table 4 Responses Relating to Load-Time Waveform (trial calculations).

Case No.	Load-Time waveform	Maximum response at slab center	
		Displacement (mm)	Main steel bar strain (μ)
1 (Basic pattern)	 0, 0.01, 0.02, 0.03, 0.06 (sec)	9.4	1,659
2	 0, 0.005, 0.20, 0.03, 0.06 (sec)	9.3	1,632
3	 0, 0.008, 0.012, 0.02, 0.03, 0.06 (sec)	11.2	1,951
4	 0, 0.005, 0.015, 0.02, 0.03, 0.06 (sec)	13.5	2,371
5	 0, 0.01, 0.02 (sec)	9.4	1,604

4.4 Response Sensitivity to the Load-Time Waveform

Where the dynamic design is based on a standard load-time waveform, the question, how the differences from the actual load-time waveform influences the calculation, becomes an issue.

Five simulations for different waveforms were carried out with a given value of the maximum impact load (Table-4). This simulation was made on Test No.1-2 in Table-3.

A comparison of cases No.1 and No.2 in Table-4 tells that the quickness of load rising influences the response only a little in this range. As pointed out by Yoshida et al.[2], it is found that a continuation of the extreme loads is the main influence on the responses, as seen by comparing cases No.1, 3, and 4. However, the continuation of the extreme values in the experiments shown in

Table-1 are much shorter than that in Case No.3 in Table-4, where the increment in the calculated response is not high, some 20% of the basic form (case No.1). Therefore a triangular load-time wave can be applied to practical dynamic designs.

To investigate the influence of the second crest of the wave on the responses, a simulation completely neglecting the second crest was made (case No.5). In result, almost same response as of the basic form was obtained (case No.1), indicating that differences in waveform on and after the second crest affect the response only little.

4.5 Simulations for An Actual Rock-shelter

This paper proposes two points for rock-shelter design method: first, to consider the increase of yield point with the strain rate in the steel bar, second, to carry out a dynamic design using a load-time waveform. To an actual design where the structure is regarded as a two-dimensional rigid frame, above two points are applied for the comparison with conventional static calculations (Figure-11) using the same uniform load as in actual designs. The load-time wave was obtained by averaging the acceleration waves in Table-1 of Calculated Lamé Values of 100-400tf/m^2.

As a result of the calculations, the bending moment of the top slab at impact loading was 62% of that at static loading while in previous tests on RC slabs, the static and impact load responses were equal in the elastic range. Such difference between section forces at the dynamic and at the static loads can occur depending on structural details; system, rigidity, and mass. Table-5 gives a comparison of the time to generate the maximum response in this rock-shelter model with that in the RC slab test No. 6-1. In the rock-shelter model, the maximum response time is about 20% earlier than in the test RC slab, so that the actual falling rock impact can be expected to give a higher strain rate (in other words a higher yield point) than the tests.

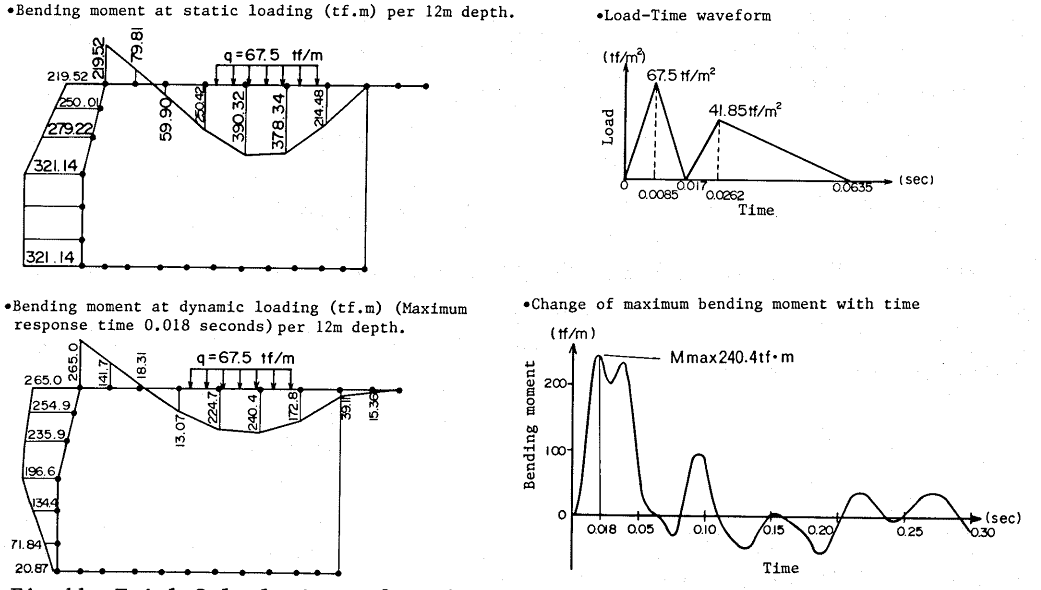


Fig.11 Trial Calculations of Bending Moment at Falling Rock Impact for Actual Rock Shelter (Comparison of static and dynamic calculations).

A trial dynamic calculation of the bearing capacity of the shelter against falling rock loads with the condition of the allowable steel bar strain of 3000μ shows that the shelter in the dynamic design can accept about four times of the falling rock load of the static design (Table-6).

Table 5 Time to Generate Maximum Response. (Unit: sec)

Case	Test No.6-1	Actual Rock Shelter Model
Time observed in tests	0.023	―――
Calculated time	0.022	0.018

Table 6 Comparison between Allowable Loads in Static and in Dynamic Designs. (trial calculations)

- Allowable stress of steel bar at falling rock loads σ_a = 1,800 × 1.7 (increment rate of ordinary allowable stress) = 3,060kg/cm^2.
- In a static designs, the steel bar stress at falling rock loads is supposed to be σ = 3,060kg/cm^2 (= σ_a).
- Assuming that 70% of the stress depends on falling rock loads, the steel bar stress due to falling rock loads σ^* is 3,060 × 0.7 = 2.142kg/cm^2, and the stress due to ordinary loads is 3,060-2,142 = 918kg/cm^2.
- The allowable strain of $3,000\mu$ is equivalent to a stress in an elastic body of σ_b = 3,000 × 10^{-6} × 2.1 × 10^6 = 6,300kg/cm^2.
- 918kg/cm^2 of σ_b (= 6,300kg/cm^2) is hold by ordinary loads, then a stress of 6,300-918 = 5,382kg/cm^2 can be allocated to falling rock loads.
- Figure-11 shows that the stress caused by falling rock loads in the dynamic design is 62% of that in the static design.
- Finally, $\dfrac{\text{Maximum allowable loads in dynamic designs}}{\text{Maximum allowable loads in static designs}} = \dfrac{5{,}382\text{kg/cm}^2}{2{,}142\text{kg/cm}^2 \times 0.62} = 4.1$

5. CONCLUSIONS

In this study, falling weight tests on RC slabs with sand cushions, reproduction of tests by F.E.M., and simulations for an actual rock-shelter were made to investigate the strength of RC rock-shelters against falling rock loads and to propose a rational design method for rock-shelters. The results are as follows:

(1) Bending deformation in span is preeminent in the response to falling weight impacts of RC slabs with sand cushions.

(2) The tests show that Lamé Value λ in the formula of falling rock impact force of the Falling Rock Protection Manual is well and inversely correlated with the rising up time of the impact force. This allowed to determine the pattern of load-time waves for Lamé Value in general 100 to 400tf/m^2.

(3) The strength against falling weight impact forces of RC slabs with sand cushions considerably exceeds that against static loads because the response of the structure under rapid and instantaneous loads does not correspond to the load changes and the structure shows its maximum response after the load has decreased. Accordingly, even when main steel bars reach their yield strain in a response, the decreasing load and the inertial force of the slab limit the increase in the strain. Simply, even when the strain of the steel bar reaches the yield range the structure maintains elastic behavior. The increase in yield

point with the rapid strain rate in the main steel bars may also contribute to improve the strength of the slab at impact.

(4). That the test results agree with the results of F.E.M. calculations makes a dynamic design of rock-shelters possible. The dynamic design method recommended in this study is mainly characterized by the following two points:
- allow the strains of members to reach higher levels considering the dynamic response of the top slab.
- apply a load based on a load-time wave to the design.

(5) Changes in the form of the first peak of the load wave give small influences on responses calculated and so increase the reliability of the dynamic design.

(6) The strength of RC slabs against falling weights was not decreased by repeated impacts with the same energy. Even if a rock-shelter sustains the maximum falling rock load estimated in the design more than once at the same spot, it remains safe.

Under the condition that strains are allowed to rise up to a greater level, the strength of RC slabs against instantaneous loads is far higher than against static loads. However, structure designs where member strains far excess the yield points, even instantaneously, may differ widely from present design concepts in civil engineering. Therefore the following method for rock-shelters protecting against falling rocks would be possible: the conventional static design is recommended for high probability light loads; "the ultimate design method against falling rock impact forces" presented in this paper is for low probability heavy loads. It is often reported that rock-shelters are attacked by much more serious falling rocks than the designed, but only suffer cracks in top slab of rock-shelter. For such rock falls with low probability and heavy loads, the design method proposed here would be acceptable. This method is also optimum in investigating strength limits of rock-shelters in service at present.

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