Conference Paper, Published Version

Yasuhara, Kazuya; Kanno, Yashunori; Wu, Zishien; Murakami, Satoshi

Fe Analysis of Coastal Cliff Erosion due to Ocean Wave Assailing

Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/100343

Vorgeschlagene Zitierweise/Suggested citation:
Yasuhara, Kazuya; Kanno, Yashunori; Wu, Zishien; Murakami, Satoshi (2002): Fe Analysis of Coastal Cliff Erosion due to Ocean Wave Assailing. In: Chen, Hamn-Ching; Briaud, Jean-Louis (Hg.): First International Conference on Scour of Foundations. November 17-20, 2002, College Station, USA. College Station, Texas: Texas Transportation Inst., Publications Dept.. S. 307-319.

FE Analysis of Coastal Cliff Erosion due to Ocean Wave Assailing

By

Kazuya Yasuhara[1], Satoshi Murakami[2], Yashunori Kanno[3], Zishien Wu[4],

ABSTRACT

The coastal erosion is divided into two categories : (i) sand erosion, (ii) cliff erosion. The mechanism and countermeasures for those two have mainly been pursued from coastal engineering point of view. Unfortunately, less attention has been paid to the cliff erosion from a viewpoint of geotechnical engineering. Rather, much attention has been directed from the standpoint of geology and geomorphology. Based on the extensive achievements on the problem in Japan which had been carried out by Sunamura (1992) using the methodology of the geomorphology, further investigation by the authors has been performed by the authors (2002) from a viewpoint of geotechnical engineering. The results by the authors include the mechanism, prediction and countermeasure with a special emphasis being placed on the cliff erosion of rocky coasts at Ibaraki Prefecture, Japan. Among them, the current paper aims at describing the successful results of prediction from the finite element analysis combined with the crack propagation theory involved in the field of fracture mechanics. This analysis requires unit volume weight, compressive strength, tensile strength, and Young's modulus of rocks consisting of the coastal cliff. It is indicated from analysis that:

1) Coastal cliffs consisting of soft rocks become unstable depending on increase in the eroded distance of the toe of cliffs. The failure of rocky coasts is more sensitive to tensile strength than to compressive strength of rocks.

2) The FE analysis considering the crack propagation in rocks can predict of the progress of failure in rocky coasts. The results from the FE analysis lead to construction of a design chart for roughly predicting the possibility of collapse when the geographical conditions at a given site and the geotechnical properties of a rock are given.

INTRODUCTION

The erosion at the coast has become chronic in Japan. The coastal erosion is generally

---

[1] Professor, Department of Urban and Civil Engineering, Ibaraki University, Hitachi, Ibaraki, 316-8511, Japan.

[2] Research Assistant, Department of Urban and Civil Engineering, Ibaraki University, Hitachi, Ibaraki, 316-8511, Japan.

[3] Graduate Student, Department of Urban and Civil Engineering, Ibaraki University, Hitachi, Ibaraki, 316-8511, Japan..

[4] Professor, Department of Urban and Civil Engineering, Ibaraki University, Hitachi, Ibaraki, 316-8511,Japan.

divided into the beach erosion and the cliff erosion. Less attention has been paid to the cliff erosion than to the beach erosion. In addition, the researches on the cliff erosion have mainly been limited to the fields of coastal engineering, geology and geomorphology, and have scarcely included the geotechnical aspects. Even in the extensive achievements for the erosion of rocky coasts in Japan which have been carried out by Sunamura(1992), less information has been described from the geotechnical point of view. Authors (1995, 1997, 1999) have been investigating the mechanism, proposing the prediction and exploring the countermeasures in the past few years. Based on the previous studies, the current paper aims to propose the design charts and the predictive manual through the results from the numerical analysis by using the finite element method incorporating the crack propagation theory. Photo.2-Izura Coast

Photo.1-Unomiaki Coast

Photo.2-Izura Coast

MECHANISM OF COASTAL CLIFF EROSION

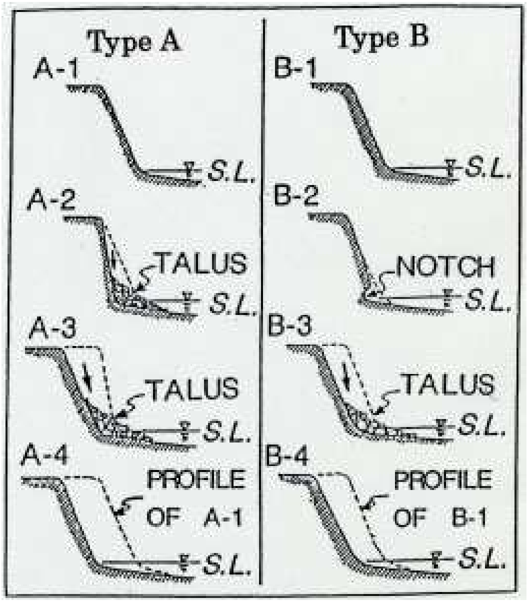


Fig.1-The process of Coastal Cliff Erosion(Sunamura)

Fig. 1 shows a typical result of the profile changes of laboratory cliffs caused by breaking waves. According to the investigation by Sunamura, the Japanese style of cliff erosions pertains to the type-B from the two types in Fig. 1. In this type, the toe of the cliff is eroded due to assailing ocean waves and the notch is formed. The rocky coast collapses when a certain distance of this notch formed due to wave actions is attained. However, the mechanism of the collapse has remained unknown. For example, no method has been found to determine whether the failure mode must be in the compressive failure or in the tensile failure. It is therefore required for taking countermeasures to deal with the situation to predict when and how the collapse initiates.

CRACK PROPAGATION ANALYSIS USING FINITE ELEMENT METHOD

The crack propagation analysis is based on the idea of the biaxial principal failure method that the crack occurs when the tensile major principal stress exceeds the tensile strength used in the analysis by considering the self-weight in whole the objective area. The analysis is characterized by:

1) the elements that undergo the crack are taken off by postulating that they are assumed not to retain their strength.
2) the analysis in the new area is repeated until the computation is converged. The

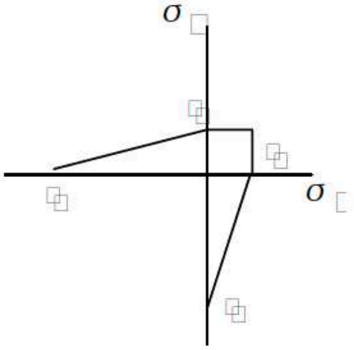


Fig.2-The Crack Generation Criteria

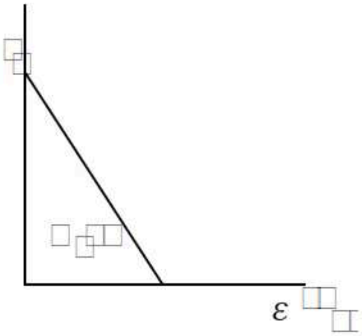


Fig.3-Tensile Softening Criteria

collapse possibility is estimated by means of the propagation condition of cracks that occur in the cliff due to the formation and development of notches.

The distributed crack model is employed in predicting the crack occurrence phenomena by means of the finite element analysis that incorporate the following:

1) The crack generation condition: this is governed by the condition as shown in Fig. 2.

2) As the softening of the material after the occurrence of the cracks, the linear tensile softening is adopted as shown in Fig. 3. The ultimate crack strain necessary to meet this condition is given by:

$$\varepsilon^{cr}_{nn.ult} = \frac{1}{\alpha}\frac{G_f^{\ I}}{h} \qquad (1)$$

where α : angle of gradient of the cliff, G_f^I : failure energy, h : equivalent converted distance of one element.

3) The shear retention after the occurrence of tension cracks is assumed to be constant, that is, β is kept constant during shearing which is equal to 0.05.

OBJECTIVE MODEL FOR TWO DIMENSIONAL ANALYSIS

Analytical Procedure

The crack propagation analysis by using a FE analysis for exploring stability of rocky coasts is performed by following the procedure as (Fig. 4):

i) Self-weight analysis for the objective rocky coast undergoing erosion at the toe of the cliff due to assailing ocean waves was conducted to find the elements where cracks occur.

ii) By assuming that the rock elements with cracks lose strength leading to failure, the new region in which the elements with cracks are eliminated is set for the successive analysis.

iii) Self-weight analysis was carried out again for the new analytical region without elements where cracks take place.

iv) This procedure from (i) to (iii) is repeated until the analytical solution is diverged.

The divergence of the solution in this procedure indicates the condition that the some elements with cracks being taken place suffer from collapse. Accordingly, the collapse seems to occur and propagate from the bottom to the top of the cliff, as is shown in Fig. 5.

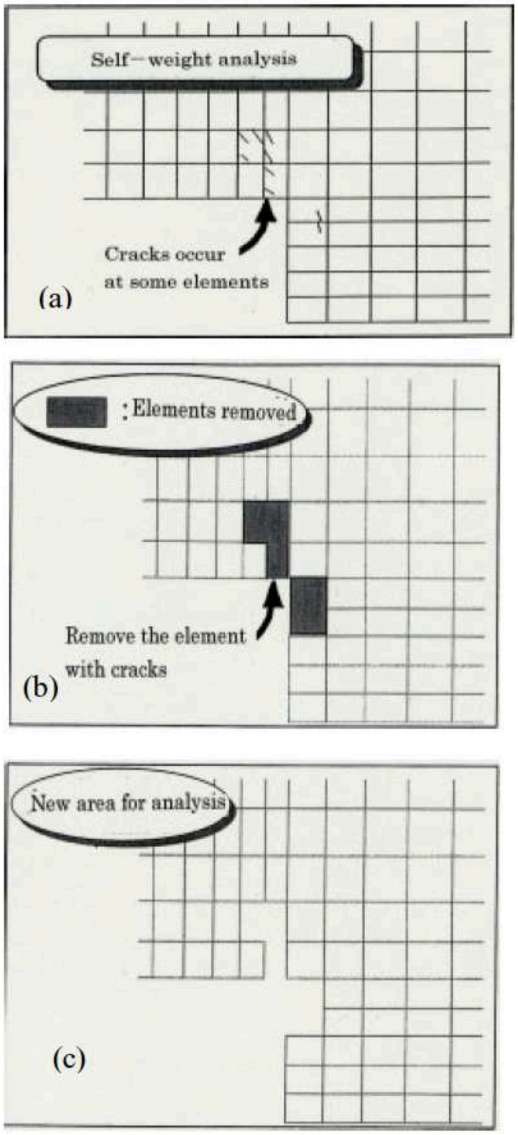


Fig.4-Analytical Procedure

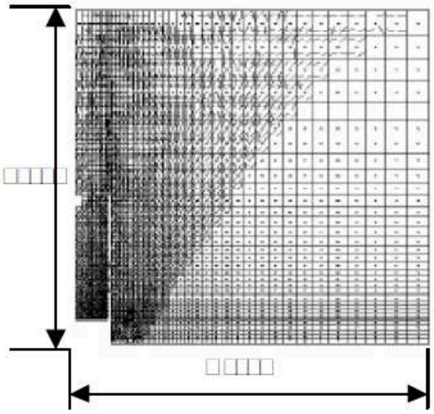


Fig.5-An Example for FE Analysis

Two-dimensional Modeling of the Objective Ground for Finite Element Analysis

For modeling the coastal cliff whose typical configuration is shown in Fig. 6, the following assumptions are employed:

i) The coastal cliff is formed by the homogeneous rock and deformation of rocky coasts occurs under the plane strain condition.

ii) Base foundations supporting the cliff consist of the extremely hard rocks.

iii) The base is constrained with the vertical and the horizontal directions, while the back face is constrained at the vertical direction only.

The two-dimensional FE analysis was conducted by changing the height of rocky coast, the gradient of the slope, and the width as is shown in Fig. 6. The width and height of the notch formed by erosion are also assumed 1m and 1m, respectively.

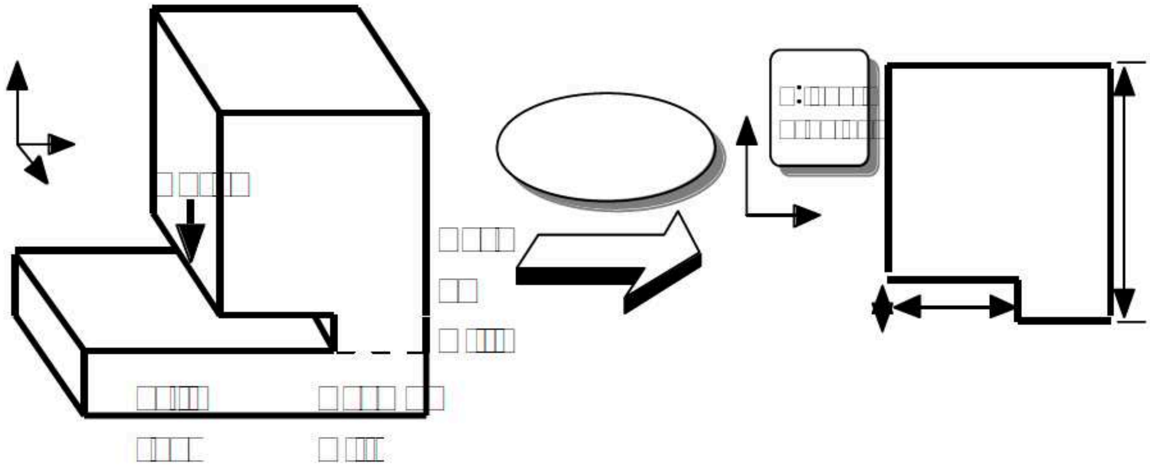


Fig6-Model for FE Analysis

SELECTION OF PRAMETERS NECESSARY FOR ANALYSIS

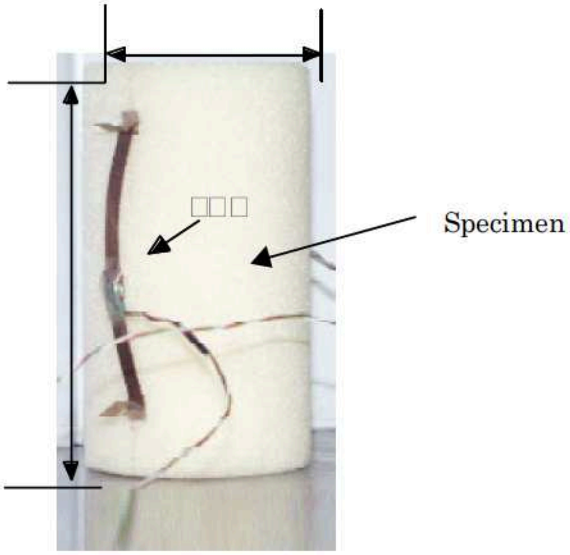


Fig.7-Specimen attached by LDT

The parameters necessary for CPA-FE analysis are : unit volume weight, compression and tensile strengths, and elastic modulus. The compressive and tensile strengths, f_c, f_t were obtained from unconfined compression and Brazilian tests, respectively, at laboratory on rock samples. The elastic modulus, E, was determined from small strain which was measured using the local displacement transducer (LDT) attached at the specimen in unconfined compression tests as shown in Fig. 7. The typical examples of the results from unconfined compression and Brazilian tests on a mudrock that was taken at the coastal cliff of the Northern Ibaraki, Japan are presented in Figs. 8a, b. A considerable difference in the elastic modulus determined from the results using the outer displacement meter and the LDT was observed. This gives the results from numerical computation based on the crack propagation analysis (CPA) as will be described in the later part of the paper.

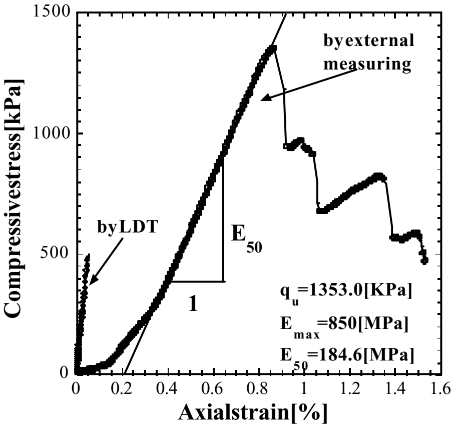


Fig.8a-Results from Unconfined Compression Test

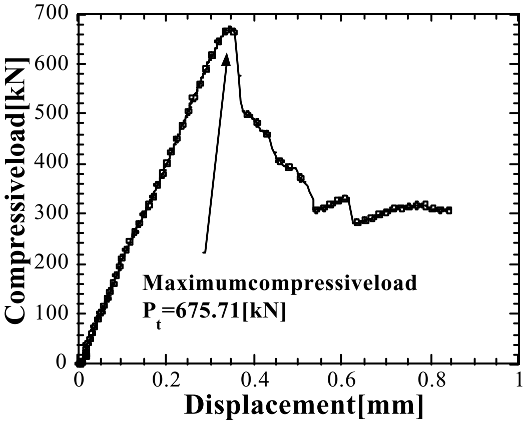


Fig.8b-Results from Brazilian Tests

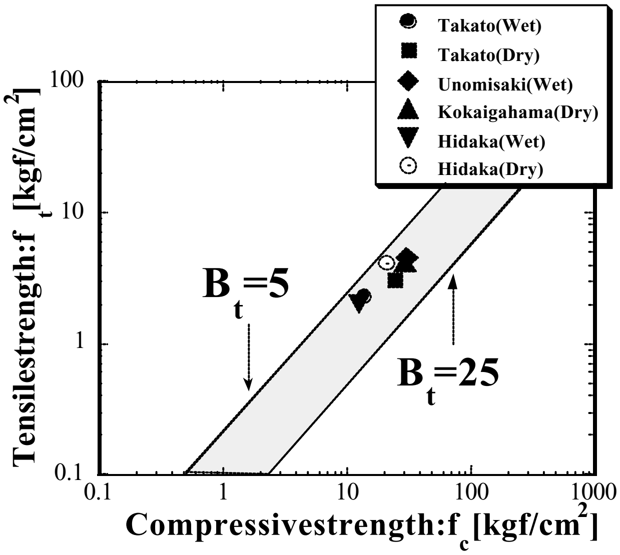


Fig.9-Relation between f_t and f_c

Among the mechanical properties, a correlation between compressive and tensile strength is presented in Fig. 9. Thus, the brittleness index, B_t, is defined by:

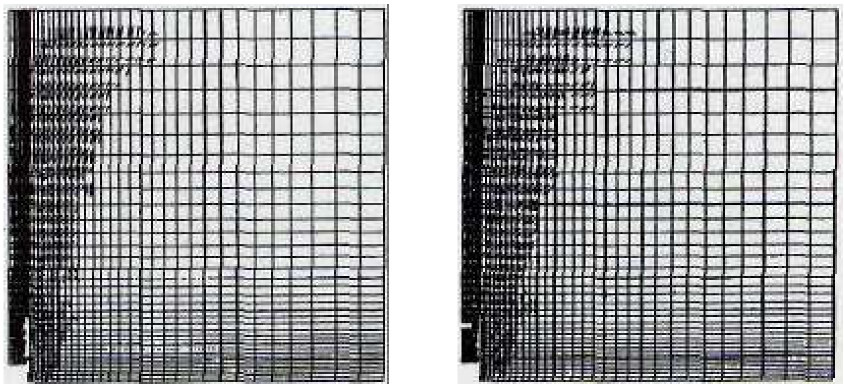
$$B_t = f_c/f_t \quad (2)$$

where f_c and f_t are compressive and tensile strengths, respectively. Fig. 9 shows the tensile strength plotted against the unconfined compression strength for the mud rocks together with the data on saturated rock samples collated by Sunamura (1991). There is a clear tendency for tensile strength, f_t, to increase with increasing compression strength, f_c. It is also found that the brittleness index, B_t, ranges from 5 to 25.

PREDICTION OF COLLAPSIBLE RISK USING CRACK PROPAGATION ANALYSIS

Results from FE Analysis

A typical result from finite element analysis using the crack propagation theory is shown in Fig. 10 which present the effects of Young's modulus on manners of crack propagation in coastal cliff and distribution of principal stresses. Those two values of Young's modulus correspond to those measured using an outer displacement indicator and a LDT. Although there is not a considerable difference in distribution of crack propagation between both values of Young's modulus, time required for computation is different with each other, three times being required for the larger Young' modulus than the smaller one. In other words, the coastal cliff with the larger Young's modulus is more stable for cliff erosion than with the smaller one.



(a)E=250[MPa] (b)E=850[MPa]

Fig.10-Effects of Young's Module on Results from FEM

DefinitionofSafetyFactor

The safety factor for evaluating a possibility of collapse of the cliff at rocky coasts is givenby:

$$D = \frac{f_{ta}}{f_t} \quad (3a) \quad or \quad F_s = \frac{1}{D} = \frac{f_t}{f_{ta}} \quad (3b)$$

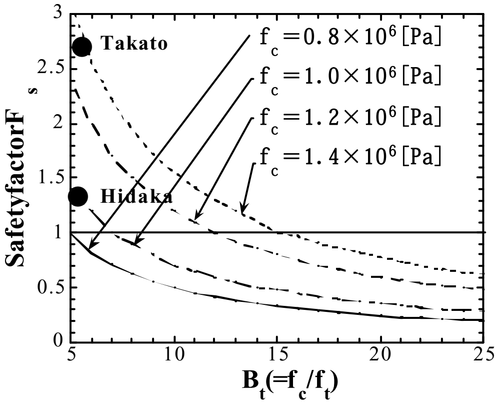


Fig.11-RelationbetweenF $_s$andB $_t$

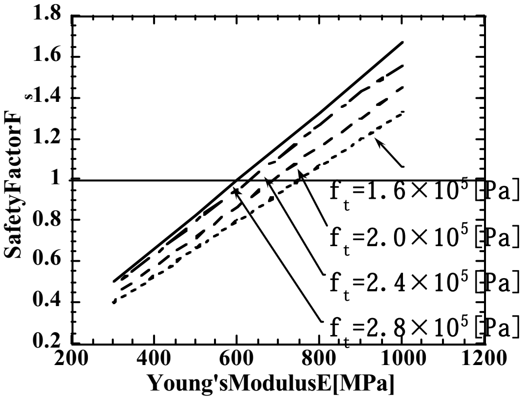


Fig.12-RelationbetweenF $_s$andE

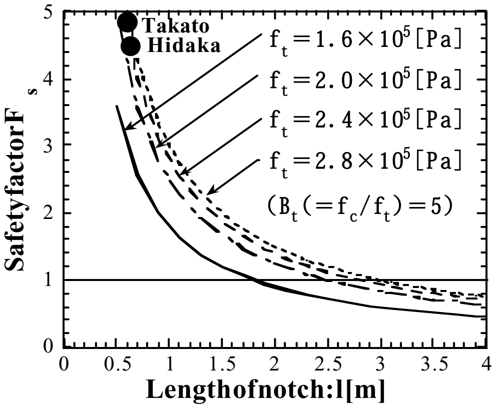


Fig.13-EffectofB $_t$ontheRelationbetweenF $_s$andtheLengthofNotch

where f_t : tensile strength at a given condition, f $_t$: allowable tensile strength of rocks which constituting of cliffs, which do not lead to collapse, D : failure potential. The results from FE analysis are given in the form of the safety factor, F_s, being plotted against the given parameters of the configuration of cliffs and the properties of rocks.

Effects of Mechanical Properties of Rocks Constituting Coastal Cliffs

Fig. 11 shows the influence of the brittleness, B_t, on the safety factor, F_s, calculated as a parameter of the compression strength, f_c. It is indicated that the safety factor decreases with increasing the brittleness and with decreasing the compression strength.

Effects of Young's Modulus of Rocks

As was previously described, the Young's modulus is an important factor influencing on the stability of coastal cliffs. The results from FE analysis are given in Fig. 12 as the relations between the safety factor and the Young's modulus.

Effects of Configuration of Coastal Cliffs

Among the effects of configuration of coastal cliffs, the eroded distance to form notch is taken as the most important one. Fig. 13 shows the relation of the safety factor plotted against the maximum eroded distance measured at laboratory tests. As far as the present situation of the eroded distance at the two coastal sites, the Takato and Hitachi coasts in the Northern Ibaraki which have suffered from severe cliff erosion is concerned, they are not situated under the serious condition to collapse of rock slope due to breaking waves.

COLLAPSE FUNCTION IN TERMS OF FE ANALYSIS

In terms of the results from the afore-mentioned FE analysis, the authors have proposed the following "collapse function" which enables us to predict quantitatively the possibility of collapse of rocky coasts under assailing ocean waves:

$$F = F(H, \alpha, f_c, f_t, l) \tag{4}$$

where H : height of cliff, a : inclination of rock slope, and L : horizontal length of notch. The possibility of collapse depends on whether F is larger or smaller than unity. Here, if the collapse function monotonically increases or decreases with increasing the values of B_t, H and L, Eq. (4) is converted into:

$$F=F(H,\alpha,f_c^{-1},B_t,l) \quad (5)$$

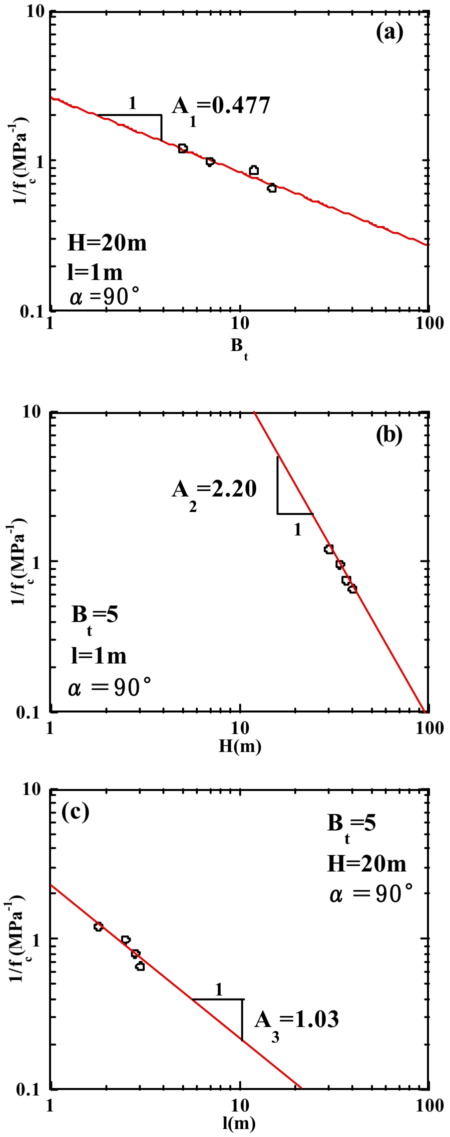


Fig.14-Effectsofinfluencingfactorson($1/f_c$)

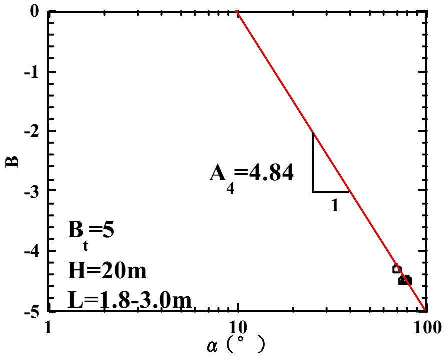


Fig.15-RelationbetweenBand α

Fig. 14 represents the interrelations between 1/f_c and one of other three parameters, B_t, H and L. If we postulate that the projection to the two parameters plane can be approximated by the curves with the same gradient when the other conditions get changed, the collapse function towards the cliff with the gradient of 90 degree for slope can be expressed by:

$$F_{90}=\ln(f_c^{-1})+A_1\ln(B_t)+A_2\ln(H)+A_3\ln(L)+A_4\ln(a)+C_{90} \quad (6)$$

$$F=\ln(f_c^{-1})+A_1\ln(B_t)+A_2\ln(H)+A_3\ln(L)+A_4\ln(a)+C \quad (7)$$

Where A_4 and C are determined from the relation between B_t and a as shown in Fig. 15. Eq.(7) can be converted into:

$$l_f=f_c\ B_t H\ \alpha\ C \quad (8)$$

When we assume the values for the Takakdo Coast, 1.2 MPa for f_c, 5 for B_t, 20m for H and 90 for $_a$, then we have L_f=3.81 corresponding to F_s = 1. This is in good agreement with the value for the allowable length of notch, L equal to 3.35m as can be read out from Fig.13.

When the erosion rate is designated by l(=dl/dt), the collapsible period, T_f, is defined by:

$$T_f=\frac{l_f}{d} \quad (9)$$

By inserting Eq. (8) into Eq.(9), Eq.(9) leads to:

$$T_f=\frac{f_c\,B\,H\,\alpha\,C}{d} \quad (10)$$

Accordingly, the collapsible period, N_T, at a certain period, T is given by:

$$N_T=<T,T_f> \quad (11)$$

where the symbol, <A, B> implies the quotient in which A is divided by B. Therefore, the retarding distance D_T of cliffs can be given by:

$$D_T=1_f N_T \quad (12)$$

Using the parameters, compression strength and tensile strength, for the five coasts in

Northern Ibaraki, the collapse frequency, T_f, collapsed cycle, N_{100}, and retarding distance, D_{100} incoming 100 years are calculated and listed in Table 1.

Table 1 Results from Calculation for 5 Coasts

	T_f(y)	N_{100}	D_{100}(m)
Izura	5.45	18	60.85
Takato	3.13	31	45.58
Kokaiga-hama	24.84	4	32.80
Hidaka	6.33	15	94.96
Ohmika	26.28	3	18.14

COCLUSIONS

1) It is verified that the collapse of coastal rocky cliffs is the tension failure mode that is governed by the tension toughness.
2) The failure potential increases with increasing the brittleness, f_c/f_t, in which f_c and f_t are compression and tensile strengths.
3) The crack propagation analysis using the finite element method can predict this failure mode. Based on the numerical analysis, the design charts are established.
4) The collapse frequency and the collapse period can be predicted using the collapse function that is defined by the results from FE analysis.

REFERENCES

1. Japan Information Proceeding: DIANA, Release 7.1, Basic Course, 1998.

2. Sunamura, T.: Geomorphology of Rocky Coast, John Wiley & Sons LTD, 1992.

3. Research Committee : Report of the Technical Research Committee on Large-scaled Collapse in Large-scaled Rock Slope, p.2, JSCE, 1997.

4. Yasuhara, K., Murakami, S., Kanno, Y., Wu, Z-S. and Kanazawa, H.: Crack propagation analysis of rock collapse due to coastal cliff erosion, Memoir of Faculty of Engineering, Ibaraki University, Vol.49, pp.32-43, 2002 (in Japanese).