CHAPTER 153

Reliability Based Design of Rubble-Mound Breakwater

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Abstract

The object of this present research is to study probabilistic design of armor blocks protecting composite breakwaters and to produce optimum design methodology for S-shaped breakwaters in terms of failure probability and construction cost. Failure probability in the vicinity of the still water level is greatest in the case of uniform sloped breakwaters. Therefore,S-shaped breakwaters of which the slope near the still water level is milder have a reduced risk of damage compared to uniform sloped ones. The optimum design index presents good economics and reliability in rubble-mound breakwater design.

Introduction

In recent years in Japan,as breakwaters have been constructed in deeper and deeper areas, armor block weights to protect caissons of composite breakwaters against wave action have also had to be increased. The block weights are generally determined using the Hudson formula with appropriate K_D values for each type of concrete block. However there are several problems in the usage of this formula in that,effects such as wave periods,probabilistic properties of wave heights and periods etc. can not be taken into account. Van Der Meer(1987) proposed formulae for calculation of stable armor units based on hydraulic model testing. These formulae can present the effects of wave periods. In addition he also produced probabilistic designs of rubble-mound breakwaters. When working group 12 of PIANC(1987) dealt with total reliability design for breakwaters including foundations,strength of armor units

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etc. and compared the results of levels I,II and III,the reliability theory for concrete blocks or armor stones was based on the formulae of Van Der Meer.

Mizumura et al (1988) proposed a theory for reliability design of rubble-mound breakwaters of level III. They calculated the incipient motion of an armor block using a simple physical model. According to them the stability of armor blocks depended on the wave periods.

In large wave areas the weight of blocks would have to exceed 100t in cases where the gradient of the protection is 1:4/3 or 1:1.5. In addition,in a case of a uniform sloped breakwater,the failure probability of concrete blocks would be greatest in the vicinity of the still water level obtained from the reliability analysis. As a result a complex sloped breakwater,a so called "S-shaped breakwater" should be utilized to increase stability. The failure probability of this S-shaped breakwater would be lower than that of a uniform sloped one. However, if an S-shaped breakwater were used,the cross-sectional area of armor blocks would become exceedingly large and the resulting construction cost extremely high. In this study,the authors introduce a simple index taking both the construction costs and failure probability of armor blocks of S-shaped breakwaters into consideration.

Method for Stability Analysis

In Japan,breakwaters like the one shown in Fig.1 are usually constructed.

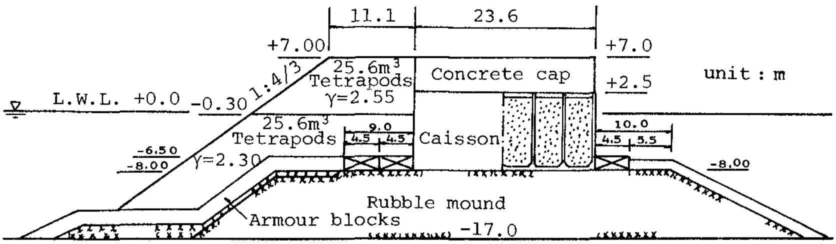


Fig.1 Typical Breakwater in Japan

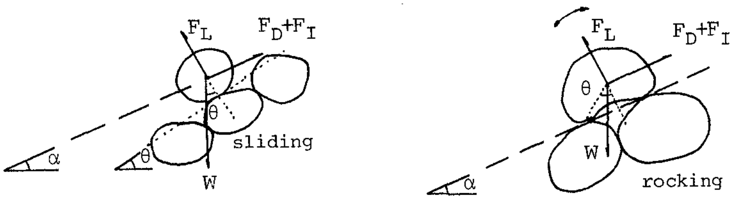
In this type of breakwater,there are many possibilities for failure,as listed in Table 1.

Table 1 Risk Elements

1) Armor layer failure
   *Movement of armor unit
2) Toe scouring and collapse
3) Caisson slide and overturning
4) Damage to structural elements
   *Fatigue of materials
   *Breakage of armor units
5) Material degradation due to chemical action
6) Others

However,it is too complicated to analyse all of the risk elements theoretically but in the case of composite breakwaters protected with armor blocks, as armor unit failure or caisson slide are the principal problems, the authors have focused on armor block motion as a first step to indicate reliability of design.

The movements of armor blocks under wave action are classified into three categories sliding, rocking and lifting-up as shown in Fig.2.



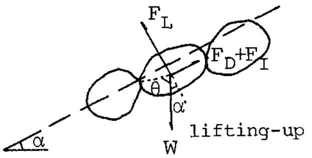


Fig.2 Motion of an Armor Unit

In this figure, F_I, F_D and F_L are the external forces due to waves and refer to the inertia, drag and lift forces respectively. α and θ are the angles of the armor block slope from the horizontal and the repose angle of blocks respectively. When a resistance force(f_R) is smaller than these external forces(f_S), an armor unit moves as expressed below.

$$\begin{array}{ll} \text{Stable} & f_R - f_S \geqq 0 \\ \text{Unstable} & f_R - f_S < 0 \end{array} \qquad (1)$$

It is considered that the external forces acting on an armor unit are induced by two kinds of waves. One is waves breaking on the slope of the protection and the other is non-breaking waves. In the case of breaking waves, the wave force is calculated using Goda's formula (Goda 1985) while in the case of non-breaking waves, it is assumed according to the small amplitude wave theory up to the run-up wave height. Details of the theory were presented by Mizumura et al (1988).

Method for Reliability Analysis

Before mentioning risk analysis, the word "Movability" of an armor block has to be defined here. When the armor block concerned is located in the condition shown in Fig.2, the block is referred to as being in a state of movability. In other words, this armor block can not be interfered with by any block in its vicinity and resistance forces consist of only gravity and frictional forces.

The following assumptions are made to connect the movability condition with stability analysis.

(1) The movable units distribute uniformly between the bottom and 90% of the significant wave height above the still water level along the breakwater slope.

(2) The number of armor blocks falling into a movability state is K.
(3) The movability state of an armor block continues for n_i sets of a combination of the wave height and period for i being 1 to K.

In accordance with these assumptions,processes (2) and (3) above can be simulated by a queueing theory. Integers K and n_i are probabilistic variables and the process can be described by the Poisson process and expressed as eqs. (2) and (3).

$$P(k)=\frac{\exp(-\lambda)\lambda^{k}}{k!} \tag{2}$$

$$P(n_i)=\frac{\exp(-\lambda')\lambda'^{n_i}}{n_i!} \tag{3}$$

where λ and λ' refer to the parameters to govern the Poisson process or its mean values.

The failure probability from each motion of an armor block can be expressed by the following equation using eq. (1).

$$P=\int_0^{\infty}\int_0^{s} f(r,s)drds \tag{4}$$

where $f(r,s)=f_R-f_S$ (5)

and f(r,s) is the so-called risk function. P indicates the failure probability of any of the 3 motions as defined i.e. sliding,rocking or lifting-up.

Before the calculation of the failure probability,distribution of some coefficients,i.e.the drag coefficient,C_D,the virtual mass coefficient, C_I ,the lifting-up coefficient,C_L and the repose angle of an armor unit etc. must be decided. These coefficients and any others that are necessary must also be treated as random variables in accordance with Mizumura et al(1988). Wave heights are assumed to be according to the Rayleigh distribution and in the case of wave periods,the square also belongs to the same distribution. The Monte Carlo method with sampling a pair of wave heights and periods from their distributions is applied to obtain the distribution of the reliability function with respect to each failure due to sliding,rocking and lifting-up.

The probability corresponding to sliding,rocking and lifting-up,referred to as P_s,P_r and P_l respectively,is calculated and the failure probability,of one armor block,$P_e(i)$,can be computed by the sum of each set,P_s,P_r and P_l as below,

$$P_e(i)=P_s+P_r+P_l-P_sP_r-P_rP_l-P_lP_s+P_sP_rP_l \tag{6}$$

if P_s,P_r and P_l are independent of each other.Therefore if the number of armor units per unit width of breakwater is written with m,the total failure probability P_W can be described as equation (7).

$$P_w = 1 - \prod_{i=1}^{m} (1 - P_e(i)) \tag{7}$$

The values of λ and λ' in eqs. (3) and (4) have to be determined. These values should be estimated using the results of the hydraulic model test performed by Tanimoto et al (1985). The trials can be made with various values of λ and λ'. Fig. 3 shows a comparison of the simulated failure probability with the result of the hydraulic model test.

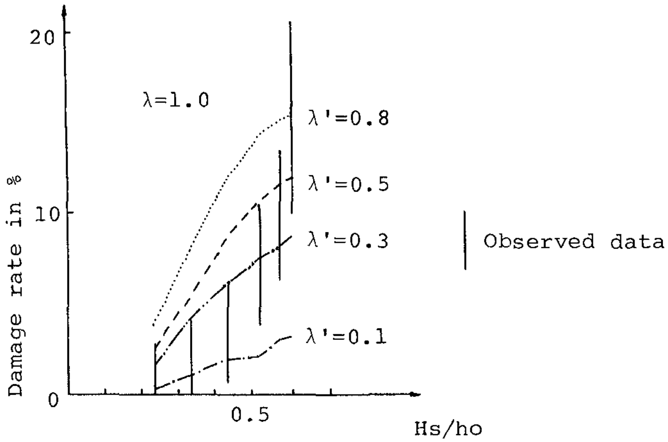


Fig.3 Comparison of Computed Relative Damage with Observed Relative Damage for Different λ' Values

From this figure,it can be seen that a λ value of 1.0 and of λ' 0.3 are appropriate and hereinafter,are used in the calculation.

<u>Failure Probability of Uniform Sloped Breakwaters</u>

Fig.4 shows a computed cross section of a breakwater.

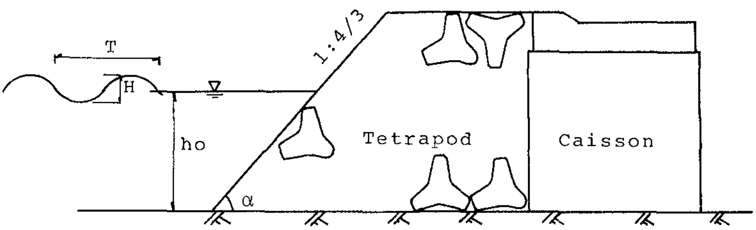


Fig.4 Sketch of Computed Cross Section of Uniform Sloped Breakwater

Tetrapods were selected as the armor blocks. The calculation conditions are summarized in Table 2.

Table 2 Calculation Conditions

Hs= 4.0 m	: $\tan\alpha$ = 0.75
Ts= 10.0 sec	: W = 7.36 t
ho= 6.0 m	
no wave overtopping	

In this Table,W indicates the weight of a tetrapod obtained using the Hudson formula.

Fig.5 shows the spatial distribution of the total failure probability along the slope of the breakwater.

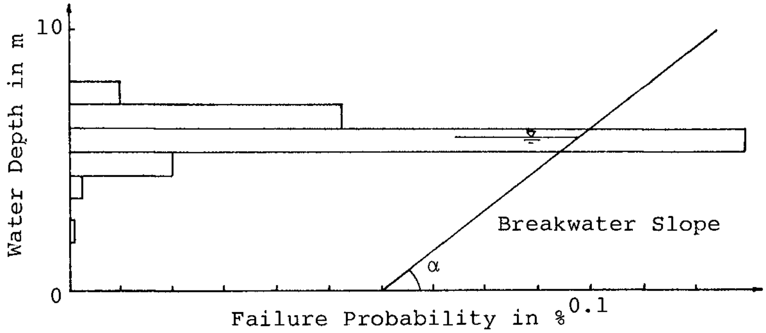


Fig.5 Spatial Distribution of Failure Probability

The risk became highest in the vicinity of the still water level as expected. This result agreed with results from hydraulic model tests and field observations conducted elsewhere except in cases of particular conditions. Therefore in any case of uniform sloped breakwaters,when armor blocks are located near the still water level,they are at more risk than in any other location.

Failure Probability of S-shaped Breakwaters

As mentioned above,the failure probability becomes a maximum near the still water level. Therefore if the failure probability in this vicinity decreased,the total risk would be reduced. An S-shaped breakwater such as the one shown in Fig.6 had to be utilized to decrease the risk of failure.

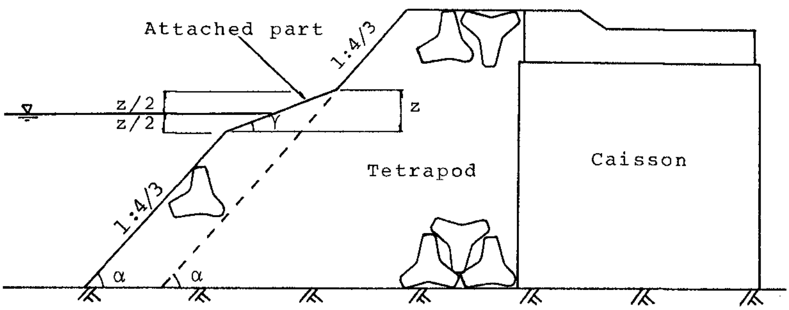


Fig.6 Sketch of S-shaped Breakwater

In this figure, γ is the angle of the attached part from the horizontal and z refers to the vertical length of the attached part.

Fig.7 shows an example of the spatial distribution of the failure probability along an S-type breakwater slope. In this calculation the values of γ and z were taken as 0.33 radians and 165cm respectively. The figure shows a failure probability significantly reduced compared with that shown in Fig.5. The beneficial effect of the S-shaped breakwater is evident.

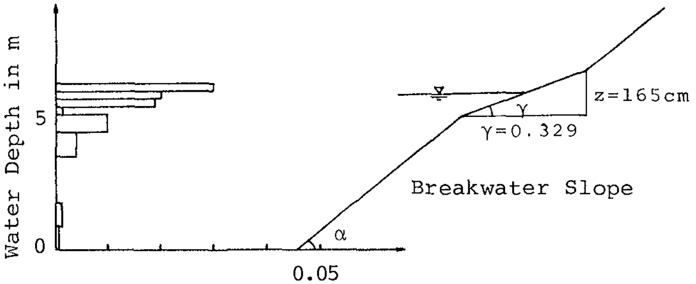


Fig.7 Spatial Distribution of Failure Probability

Fig.8 shows the failure probability of an S-shaped breakwater taking z as a parameter under the same calculation conditions as listed in Table 2.

Saville(1958) obtained run-up heights for composite sloped breakwaters,so in our calculation the run-up wave height was computed according to his method. In the range of small γ ,the failure probability of small z was larger than that of large z. This meant that in the case where the gradient of the attached slope was milder,if the slope was longer,the risk would be reduced. When γ became larger,the failure probability of a small value of z e.g. 15cm became lower and where z≈165cm,it increased. Therefore in a range of large γ,it was seen that failure probabilities converge into one. Thus,the failure probability of an S-shaped breakwater varies in terms of z and γ and it becomes unclear how to decide the values of z and γ. In addition

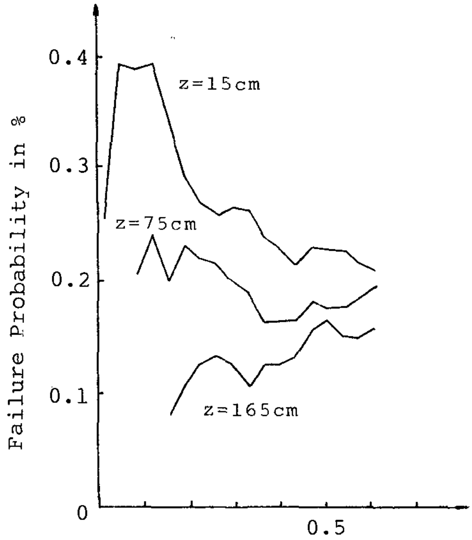


Fig.8 Failure Probability for S-type Breakwater

values of γ and z affect the area of the breakwater section and the construction cost is affected.

Optimum Design Index

An optimum design breakwater has to satisfy in terms of both reliability and economics. However the construction cost depends on the cross sectional area. From this view point,the authors employed an optimum design index,I,as expressed by the following equation under the simple assumptions that construction cost is proportional to cross sectional area.

$$I = \frac{1}{2}\left(\frac{P_f}{P_{f_o}} + \frac{A}{A_o}\right) \tag{9}$$

in which I is the optimum design index,P_f is the failure probability of an S-type breakwater,P_{fo} indicates the same for a uniform sloped type,A shows the cross sectional area of the S-shaped breakwater and Ao is the area of a uniform sloped one.

This index is very simple and implies that the weight of armor block stays the same. The index,however,is appropriate at this stage of design. The optimum design is made by employing γ and z values making I a minimum.

A cross sectional area is shown in Fig.9. The calculation conditions are the same as mentioned previously.The figure indicates the changes in the cross sectional area against γ with fixed z value. In the case where z=165cm, the cross sectional area is much larger than that in the case where z=15cm. So,the construction cost would be extreme for the greater value of z,while the failure probability shown in Fig.8 in the case where z=165cm is lower than that of the smaller z value.

Fig.10 shows the optimum design index,I.

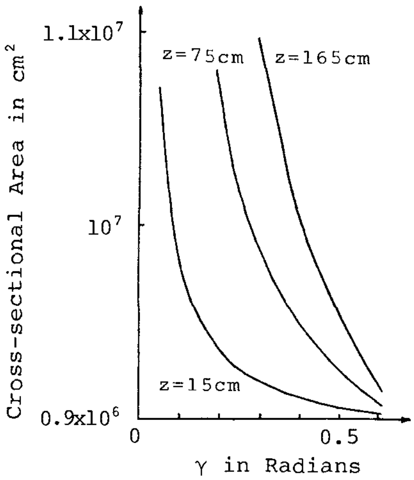


Fig.9 Cross-sectional Area for S-type Breakwater

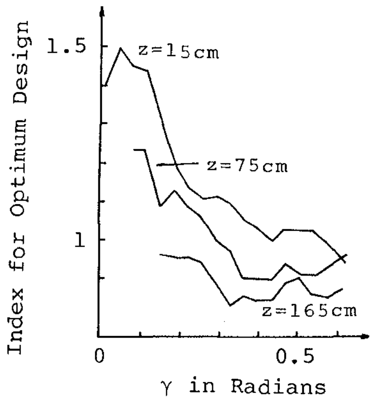


Fig.10 Index for Optimum Design

I is small for large z values. When z and γ become smaller, I becomes greater. This fact suggests that the attached part requires a gradient, i.e. the attached part is not always level. In the optimum S-shaped breakwater, the minimum value of I is 0.83 when γ is 0.33 and z is 165cm. P_f/P_{fo} and A/Ao are calculated as 0.48 and 1.18 respectively. The spatial distribution of the failure probability of an S-type breakwater has already been shown in Fig.7. Thus, from the sample calculation, although construction of an S-type breakwater requires a mere 18% cost increase, the reliability becomes twice as good as that of a uniform sloped breakwater.

Fig.11 shows relationship between the significant wave height and γ, z, the failure probability and volume of protection part when the optimum design index, I, is a minimum in the case where the wave period and block weight are fixed at 10sec and 8t respectively.

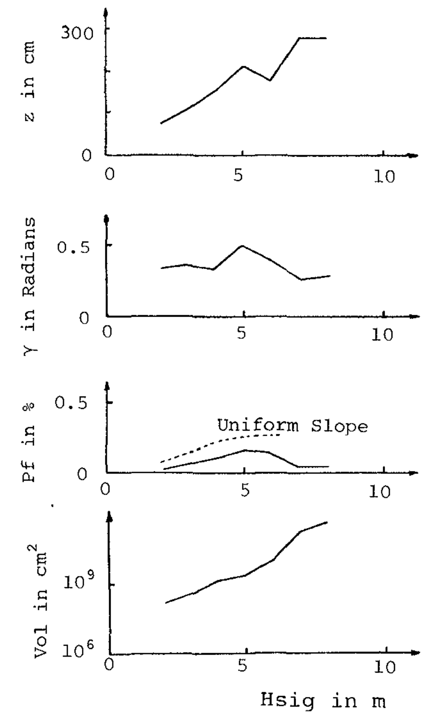


Fig.11 Relationship between H_{sig} and z, γ, P_f and Vol. when I is Minimum

In the graph of P_f, the broken line indicates the failure probability for a uniform sloped breakwater. If a uniform sloped breakwater is used, the risk of failure increases as indicated by the dotted line in terms of the incident wave height. In the case of an S-type breakwater, however, in a range of wave height higher than 5m,the failure probability would be reduced by employing γ as less than 0.5 and z greater than 200cm. Thus, this figure proves useful for the optimum design of the S-shaped breakwaters when the design wave height changes.

Fig.12 indicates changes in the failure probability,γ, z and the volume of cross section when I is a minimum in terms of the wave period under the conditions where the wave height and weight of the armor block are fixed at 4m and 8t respectively. In the condition where T_{sig} is less than 10sec,the optimum design is made by employing γ of 0.3-0.5 radians(the gradient of the attached part is 1:1.8-1:3.2) and z being 110cm-130cm. In the case where T_{sig} is 10sec-20sec,I became a minimum by keeping γ as 0.5(the gradient is 1:1.8) and z of 130cm. In this range of T_{sig},the failure probability gradually increases and is less than that of the uniform sloped breakwater. Thus even though the wave period becomes longer,it is not necessary to enlarge the protection part to ensure the same reliability for an S-Shaped breakwater.

Fig.13 shows the influence of armor unit weight to the volume,the failure probability, γ and z under the condition where I is a minimum by holding the wave height and period constant as 4m and 10sec respectively.

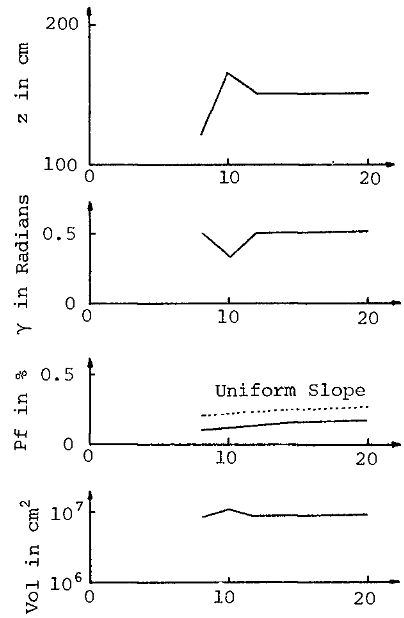


Fig.12 Relationship between T_{sig} and z,γ,P_f and Vol.when I is Minimum

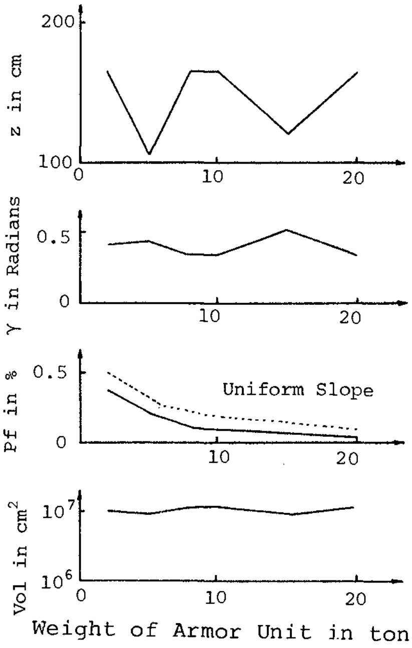


Fig.13 Relationship between Weight and z, γ,P_f and Vol.when I is Minimum

As the weight of armor unit increases,the failure probability decreases because the armor unit weight directly affects the resistance against the three kinds of block motion described previously. The volume of the protection part is almost constant when the armor unit weight becomes great. Therefore even if the weights of armor blocks increase,the construction cost does not become any higher.

As mentioned above in the optimum design,it is the wave height that most influences the construction cost and reliability compared with both the wave period and weight of armor block. Therefore if the design wave period is lengthened when designing an S-shaped breakwater,the cross sectional area need not be enlarged.

Conclusions

The following conclusions have been derived from this study.

1.The failure probability along the slope of the protection part was confirmed to be a maximum in the vicinity of the still water level in the case of a uniform sloped breakwater with armor blocks.

2.In the case of an S-type breakwater, the failure probability near the still water level became significantly lower than that of a uniform type. As a result the total risk is reduced significantly compared with that of a uniform sloped breakwater.

3.The optimum design index proposed in this study can describe both the reliability and economics of the S-shaped breakwaters. This index is most useful in producing optimum designs of breakwaters protected by armor blocks.

4.Simple calculations show that a small increase in construction expenditure results in greatly enhanced reliability.

5.The significant wave height has much more influence on construction cost than ether the wave period or block weight when the optimum design index is a minimum.

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