CHAPTER 75

MONITORING MOUND BREAKWATERS. THE CASE OF SINES

F. ABECASIS [1] and C. PITA [2]

ABSTRACT

The aim of monitoring mound breakwaters is presented. Available techniques and Sines breakwaters monitoring program are described.

INTRODUCTION

It is normal that damage occur in mound breakwaters. However, in order to avoid the inoperationality of the structures or too expensive repairs, it is essential that these damages do not overpass certain thresholds. It is therefore necessary to carry out systematic monitoring of these structures; this will allow not only the opportune correction of any deficiency but also the diagnosis of the origin of this deficiency in order to its future correction. And it must not be forgotten that the monitoring is too a valuable source of knowledge for future designs of this kind of structures.

So, in the authors' opinion, the main scope of monitoring a breakwater is to foresee and to plan maintenance works; and it is important to take into account that any repair works of a breakwater are slow and only possible with relatively calm weather. This is why maintenance works must be planned without delay after the first signs of degradation and must be carried out in the next suitable opportunity.

As a matter of fact, the possible observation of a mound breakwater is the observation of its enveloping layers, namely of the position and integrity of the outer blocks. It is not difficult to observe in such a way the part of a breakwater above the sea level; this is not the

1 - Partner, HIDROTÉCNICA PORTUGUESA, Consulting Engineers
2 - Partner, WW, Consulting Engineers

same for the submerged part, in consequence of the turbulence and the low transparency of the water. However this is the most vulnerable zone of the structure, mainly the zone just below the sea level.

TYPES OF DAMAGES

The possible types of damages in mound breakwaters are the following (Per Bruun, 1982 and Pita, 1984), see figs. 1 and 2:

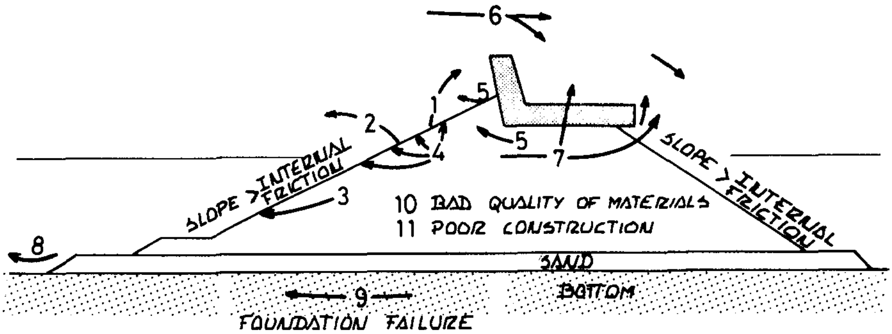

Figure 1

1 - Going out of armoring blocks due to plunging breaking of the waves on the outer slope, with subsequent displacement of blocks, generally upwards.
2 - Going out of armoring blocks due to underpressures caused by the combination of the effects of going down waves with incoming breaking waves and with hydrostatic forces of the water existing inside the mound.

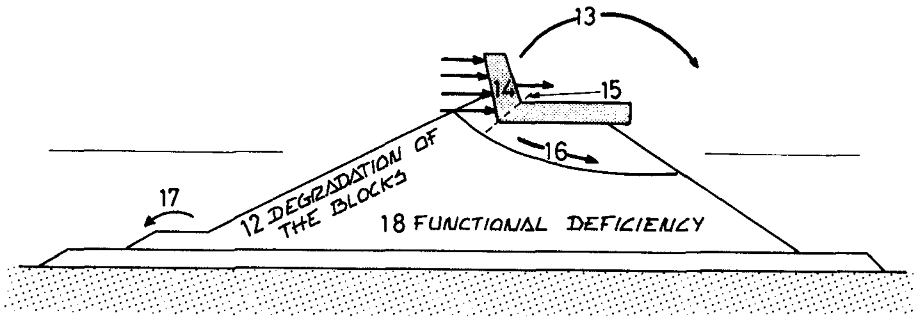

Figure 2

3 - Sliding of the armor layers. It happens often for very steep slopes or for very porous armor layers. It may be due to lack of support originated by berm deterioration (damages type 17).
4 - Falls or breakages of rocking blocks.
5 - Undermining of superstructure if it exists. The undermining may have several origins (differential settlements of the core, loss of fine elements, etc.).
6 - Instability of the top layers (and of the superstructure when it exists) and of the inner slope, due to overtoppings.
7 - Instability of the top layers (and of the superstructure when it exists) and of the inner slope, due to high underpressures. This may happen in consequence of too high porosity of filters and core.
8 - Bottom erosion in the base of the slope in consequence of wave action and/or currents.
9 - Rupture of the foundation.
10 - Damages provoked by bad quality of materials used.
11 - Damages originated by differences between the structure designed and the structure actually built, either in consequence of construction errors, or in consequence of adaptations of the design.
12 - Loss of weight and modifications in material properties due to chemical attack by sea water, to abrasion or to cavitation.
13 - Overturning of the curtain-wall, caused by the impact of waves.
14 - Sliding of the curtain-wall, caused by the impact of waves.
15 - Rupture of the superstructure, caused by wave action.
16 - Sliding of a wedge of the inner slope of the breakwater.
17 - Damages, by wave action, in the berm of support of the armor of both slopes (with possibility of damages of type 3).
18 - Functional deficiency of the structure, that is, loss (eventually temporary) of capacity of accomplishing its functions. This happens, for instance, when overtopping occur originating lack of shelter conditions inside the port.

OBSERVATION TECHNIQUES

General Comments

The approach used to monitor a mound breakwater is quite different from the approaches used in other structures.

A mound breakwater is a "collection" of thousands of blocks "randomly" placed, each one submitted to a different load and supported into a different way. It is impossible to identify a limited number of points representative of the stability of the breakwater, where forces, stresses and movements could be measured. To get these data, a large number of instrumented blocks would be required. Measurement devices acquisition and maintenance costs would be very high. Even if they were positioned, there would be a high probability of loosing an important part of them if a major storm occurs.

It must be noted that to obtain relevant data, monitoring of a breakwater must be done on a permanent basis. In these conditions, simple and not expensive techniques must be used.

The information collected with a monitoring program should be completed by a wave and current measuring campaign, so that correlations between loads and breakwater behavior are possible. As the available measuring techniques for waves or currents are very well described in several documents, only the techniques of monitoring a breakwater are described in this paper.

Available Techniques

A - VISUAL OBSERVATIONS

This technique is easy to perform frequently and regularly from the top of the structure or from a ship, specially in what concerns the emerged zone . Visual observation of the submerged zone is done by divers.

Anyway, this technique has some drawbacks:

* Damage is only detected when a certain level of it is reached;
* A detailed control of the submerged zone is difficult, due to turbulence and visibility problems.

The results of these observations can be influenced by the observer's criterion. To reduce this risk, a form must be fulfilled by the observer in accordance to the criteria presented in tables I and II. These criteria are adaptation of damage criteria used in model tests by Delft Hydraulics and by LNEC.

An important information collected easily and with sufficient accuracy by visual observations is the occurrence of overtoppings. In this case, it must recorded:

* The date/hour at which overtopping begins and ends;
* Location of overtopping and its direction of propagation along the breakwater;
* Overtopping intensity and frequency,in accordance to classification presented in table III;
* Distance from the crownwall reached by the overtopping.

TABLE I
REMOVED BLOCKS CLASSIFICATION

DEGREE	IDENTIFICATION	DESCRIPTION
0	Inexistent	There are not removed units or gaps in the armor layer.
1	Slight	Removed less than 1% of the units of upper layer of the armor. Gaps in this layer do not exceed 3 units.
2	Little	Removed less than 2% of the units of upper layer. Gaps in this layer do not exceed 3 units.
3	Moderate	Removed less than 3% of the units of upper layer. Gaps in this layer of 3 to 5 units.
4	Much	Removed more than 3% of the units of upper layer. Large gaps in this layer (more than 5 units).
5	Serious	Large gaps in the upper layer. Gaps in the second layer.
6	Destruction	The two armor layers were removed.

Note: Gap of X units: Removal of X adjacent blocks to positions distant from the original position more than a characteristic length.

TABLE II
BREAKAGE CLASSIFICATION

DEGREE	IDENTIFICATION	DESCRIPTION
0	Inexistent	There are no broken units.
1	Hardly Any	Existing breakage has only a small effect on the weight and shape of armor units.
2	Slight	Broken units do not exceed 1% of the total number of units. No more than 3 adjacent broken units.
3	Small	Broken units do not exceed 2% of the total number of units. No more than 3 adjacent broken units.
4	Moderate	Broken units do not exceed 3% of the total number of units. The number of adjacent broken units is 3 to 5.
5	Many	Broken units do not exceed 5% of the total number of units. The number of adjacent broken units do not exceed 10
6	Serious	Broken units exceed 5% of total number of units. There are 10 or more adjacent broken units.

Note: Broken unit is a unit with a weight reduction of 10% or more of its original weight, or with an important change on its original shape.

TABLE III
OVERTOPPING FREQUENCY AND INTENSITY

DEGREE	IDENTIFICATION	DESCRIPTION
0	Inexistent	No overtopping.
1	Hardly Any	Some waves produce a slight overtopping of "white water".
2	Little	Frequent overtopping of "white water". There is no "greenwater" overtopping.
3	Moderate	Some waves produce the passage of "green water" over the structure, but water quantities are not important.
4	Strong	Frequent overtopping of "green water", but water quantities are not important.
5	Very Strong	A few waves produce large overtopping water quantities.
6	Serious	Frequent overtopping of large water quantities.

B - PHOTOGRAPHY

Systematic photography of the breakwater at same scale and obtained from pre-defined points (to permit superposition of photos obtained at different observations) is an important tool to evaluate damage long term increase. These photos can be obtained from the crown of the breakwater or from a ship.

Photographic campaigns must be done in conditions that a photogrammetric treatment of the photos is possible, to evaluate the levels of the external surface of the breakwater.

C - TOPOGRAPHIC TECHNIQUES

Emerged area of the breakwater can be controlled by topographic record of the three coordinates (X,Y,Z) of selected points. As much as possible, the choice of these points must take into account the possibility of obtaining cross profiles of the breakwater (using sounding results for the submerged part).

D - SOUNDING

To quantify data on the behavior of the underwater part of the breakwater, sounding techniques must be used. The easier and less expensive technique is the manual sounding, done by a diver or from a ship. In both cases, the depths are measured in selected points located on lines perpendicular to the breakwater. The sounding with a diver has the advantage of visual observation and control of the actually sounded points (specially important in the case of a rubblemound breakwater, where the sound can be done in the vertical of a unit or in the void between adjacent units).

More sophisticated sounding techniques involve the use of side scan sonar. They can be used to obtain cross profiles or 3-D restitutions of the underwater part of the structure. The use of 3-D scanning has difficulties, because measures are influenced by the effect of wind, waves and currents on the movement of the ship.

E - AERIAL PHOTOGRAPHY

Aerial photography is a very interesting complement of other techniques, specially because good restitutions of emerged zone can be obtained with photogrammetric treatment.

F - UNDERWATER VIDEO RECORDING

Underwater video recording has two main objectives:

* To record divers observations;
* When obtained from a remote operated vehicle (ROV), to permit the observation of areas not accessible to divers.

G - TESTS OF THE MATERIALS

To evaluate the deterioration of materials there are two possible kinds of tests:

* <u>Non-destructive techniques</u>, like the use of ultra-sounding equipment and sclerometers.
* <u>Destructive techniques</u>,where some samples are collected for laboratory tests.

<u>Identification and Quantification of Damages</u>

No one of described techniques gives accurate information about the integrity of the breakwater. Anyway, with the simultaneous use of two or more techniques, it is possible to obtain reliable data to identify and quantify the several types of damages on mound breakwaters, described before. In table IV a synthesis of the use of these techniques for each type of damages is presented.

To make easier the treatment and analysis of collected data, the breakwater shall be considered split into small parts, with lengths of about 50 meters, each one being separately monitored.

THRESHOLDS FOR THE SEVERAL TYPES OF DAMAGES

An attempt has been made to establish, for the several types of damages, thresholds above which it is considered necessary to carry out normal maintenance works, short term repair works (i.e. works to be carried out when the sea conditions or the constructive

TABLE IV
OBSERVATION TECHNIQUES

DAMAGE	DESCRIPTION	POSSIBLE OBSERVATION TECHNIQUES
1 2	Removal of armor units	A - Visual observation (emerged and submerged zones). B - Photography, eventually with photogrammetric treatment. C - Traditional topographic techniques. D - Sounding techniques. E - Aerial photography, eventually with photogrammetry (emerged zone). F - Submarine television.
3	Sliding of armor layers	
4	Falls or breakages produced by rocking	
16	Sliding of a wedge of the inner slope	
5	Undermining of superstructure	A - Visual observation. B - Photography. C - Traditional topographic techniques. E - Aerial photography. G - Destructive tests
6 7 13 14 15	Instability of top layers and crownwall	A - Visual observation. B - Photography. C - Traditional topographic techniques. E - Aerial photography.
8	Bottom erosion	A - Visual observation (by divers). D - Soundings. F - Submarine television.
9	Rupture of foundation	
17	Damages in the berm of support of the armor of both slopes	
10	Bad mechanical properties of materials	A - Visual observation. G - Non-destructive tests. G - Destructive tests.
12	Physical and chemical deterioration of the materials	
18	Functional deficiency	Visual observations.

constraints allow) or as quick as possible repair works (even with provisional character and, therefore, designed for a very short life - only a few months).

These proposed thresholds, presented in table V, are based on the existing experience; as a matter of fact, they suffer very much from subjectiveness and therefore they will certainly require corrections and adjustments in the future.

TABLE V
THRESHOLDS OF DAMAGES

<table>
<tr><th rowspan="3">Damage

type</th><th rowspan="3" colspan="2">Description</th><th colspan="3">Thresholds</th></tr>
<tr><th rowspan="2">Of normal
maintenance</th><th>Of repair</th><th></th></tr>
<tr><th>Short term</th><th>As quick as possible</th></tr>
<tr><td>1

2</td><td colspan="2">Going out of armoring blocks (outer and inner slopes)</td><td rowspan="2">Degree 1 falls or lacks of blocks</td><td rowspan="2">Degree 2 falls or lacks of blocks</td><td rowspan="2">Degree 3 or above falls or lacks of blocks</td></tr>
<tr><td>3</td><td colspan="2">Sliding of the armor layers</td></tr>
<tr><td>4</td><td colspan="2">Falls or breakages of rocking blocks</td><td>Degree 1 falls or degree 2 fractures</td><td>Degree 2 falls or degree 3 fractures</td><td>Degree 3 or above falls or degree 4 fractures OR degree 2 falls and degree 3 fractures</td></tr>
<tr><td>5</td><td colspan="2">Undermining of superstructure</td><td rowspan="3">If tendency to their occurrence is detected, periodical recharges or repairs must be carried out</td><td rowspan="3">When detected</td><td rowspan="3">When detected, if if this detection happens in the beginning or during winter</td></tr>
<tr><td>6

13
14
15</td><td colspan="2">Instability of top layers or of superstructure, due to the impact of waves or to overtoppings</td></tr>
<tr><td rowspan="2">7</td><td rowspan="2">Too much porosity of filter layers or of core</td><td>Instability of top layers or of superstructure</td></tr>
<tr><td>Instability of inner slope</td><td>Degree 1 falls or lacks of blocks</td><td>Degree 2 falls or lacks of blocks</td><td>Degree 3 or above falls or lacks of blocks</td></tr>
<tr><td>8</td><td colspan="2">Bottom erosion</td><td>-</td><td>If there is fear that foundation be affected</td><td>If the foundation is affected</td></tr>
<tr><td>9</td><td colspan="2">Rupture of foundation</td><td>-</td><td>-</td><td>When detected (1)</td></tr>
<tr><td>10

12</td><td colspan="2">Materials deterioration</td><td>When detected, even small</td><td>When the material strength of blocks or other important structural elements is reduced 30%, or the weight of 3% of the blocks is reduced 40%</td><td>-</td></tr>
<tr><td>11</td><td colspan="2">Differences between the structure designed and built</td><td>-</td><td>When detected, if the studies on the structure behavior show that the structure actually built is not stable for the design wave</td><td>-</td></tr>
<tr><td>16</td><td colspan="2">Sliding of a wedge of the inner slope</td><td>-</td><td>When detected</td><td>When detected, if this detection occurs in the beginning or during winter</td></tr>
<tr><td>17</td><td colspan="2">Damages in the berm of support of the armor of both slopes</td><td>When detected, even small</td><td>If the support function of the berm is affected</td><td>If the support function of the berm is seriously affected</td></tr>
<tr><td>18</td><td colspan="2">Functional deficiency</td><td>If it causes drawback to harbour operativeness</td><td>-</td><td>-</td></tr>
</table>

(1) - In this case immediate repair is required. This repair would probably be definitive.

MONITORING SINES BREAKWATERS

Brief Description of the Breakwaters

Sines is an artificial harbor, with shelter conditions obtained with two large breakwaters.

Main breakwater,the so called West Breakwater, is also the harbor oil terminal and has several cross-profiles:

* **Type A** - Along 173 meters, it is characterized by a single layer armor of 40 tons Antifer cubes, with a slope 2:1. Top of the armor is at +14,0 m CD.
  - Concrete crown wall has a top level of +16 m CD with an external vertical face.
  - Design wave is Hs = 9 m.

* **Type B** - Along about 317 meters, this profile is composed by a double layer armor of 40 tons Antifer cubes with a slope of 2:1. Armor top is at +17,5 m CD, with a 15 m wide berm. The toe is composed by a 10 meters wide berm of 40 tons Antifer cubes.
  - The superstructure has a crown wall, with an initial part with external vertical face and top at +16m CD, and a final portion with a curved parapet to reverse the run-up flow with a top level of +19 m CD.
  - Design wave height is Hs = 9 meters.

* **Type C** - Along about 450 meters, this profile has a double layer armor of 90 tons Antifer cubes extending from levels +18 m CD to -20 m CD, with a composite slope:
  - From +18,0 m CD to -3,0 m CD → Slope 2:1
  - From -3,0 m CD to -5,0 m CD → Slope 8:1
  - From -5,0 m CD to -20,0 m CD → Slope 3:1.
  - Inner slope is composed by 3 - 6 tons quarry stones at 4:3, between levels +1,4 m CD and -15,0 m CD. Below this level, a quarry run material with a slope of 4:3 is used.
  - Superstructure is similar to the one described for the outer part of type B profile.
  - Design wave height is Hs = 14,0 m.

* **Type D** - Along 500 meters, this section is composed by a composite slope of 2 armor layers of 90 tons Antifer cubes, reaching levels of +13,2 m CD at the top and -20,0 m CD at the bottom. Slopes are as follows:
  - Between +13,2 m CD and +5,84 m CD → 3:1
  - Between +5,84 m CD and -7,0 m CD → 2:1
  - Between -7,0 m CD and -11,0 m CD → 7:1
  - Between -11,0 m CD and -19,85 m CD → 3:1

- Inner slope is composed also by 2 layers of 90 tons Antifer cubes with a slope of 3:1 between levels +13,2 m CD and +9,0 m CD and 2:1 between levels +9,0 m CD and -1,0 m CD. Below level -1,0 m CD, 9 - 12 tons quarry stones were used with a slope of 3:2 until level -4,0 m CD and 2:1 between this level and the bottom.

- The head of the breakwater armor is composed by high density 105 tons Antifer cubes.

The initial West Breakwater was 2 kilometers long. The final part, between profile type D and the previous head, around 280 meters long, will be abandoned.

The second breakwater, East Breakwater, gives shelter conditions for the operation of a coal terminal, is about 1100 meters long in depths of about 25 to 30 meters in a sand bottom. This breakwater has a double layer armor of 60 tons Antifer cubes with a slope of 2,5:1, between +14,25 m CD and -11,75 m CD. At the toe, this armor is supported by a 9 - 12 tons quarry stones berm 10 m wide.

Inner slope is composed by a 60 tons Antifer cubes armor at 3:2 between levels +12,5 m CD and -5,0 m CD.

The top of this profile is 6,25 m wide and has an in situ concreted cap platform.

The Monitoring Plan

First of all, it is recommended that the two breakwaters will be divided into reaches 30 m long.

The following observations of the two structures must be carried out:

A - Routine observations

A.1 - Visual observations

To be carried out monthly between October and April and in midsummer, in a total of 8 observations per year. They must be performed by walking on the crest of the breakwaters during low tide and recording the results. These observations must be complemented through identical procedure from a small boat, also during low tide, parallel to both slopes of the breakwaters.

Yearly (in the early spring) an observation of the submerged part of the breakwaters must be carried out. This observation will allow the completion of the program with data concerning the submerged part.

A.2 - Photography

In the beginning of spring and autumn, the visual observations from the crest and the boat referred to above must be complemented with local photos of each reach. These photos must be obtained in low water, concerning only the outer slope and the superstructure.

Yearly, in early spring, general photos of the outer slopes must be taken, also during low tide, from a boat moving parallel to the breakwaters at a distance of 150 m. These photos must allow the obtention of amplifications at constant scale, not below 1:500, for superposition with other ones obtained previously, to identify block displacements. In the same occasion, local photos of the submerged part of the slopes must be obtained to illustrate eventual deficiencies of the armor.

In what concerns the inner slope, the general and local photos will be taken only every two years, unless if the visual inspection referred to in A.1 would have shown any damage; in this later case photos of the two types must be taken. However, taking into account that east breakwater and the reconstructed part of the west one will be overtopped frequently, the general and local photos of their inner slopes must be taken with the same frequency than for the outer slopes, that is to say, general photos yearly, in early spring, and local photos twice a year, in April and September.

A.3 - Topographical techniques

Twice a year, in April and September, it must be carried out the topographical control, with basis in points in land, of one point in each module (15 m long) of the superstructure of the West Breakwater. In East Breakwater, without superstructure, it is considered enough the topographical control of one point every 30 m.

These points, in both breakwaters, will serve for the location of cross-sections of the part above water level. It is recommended the obtention of these cross-sections, once a year (in April), 60 m apart.

A.4 - Soundings

Soundings must be carried out, by any of the procedures described before, prolonging as much as possible the sounding of the submerged part of the breakwaters, both near the water surface and seaward of the base of the slope (in this later case not less than 30 m beyond this base). These soundings must be carried out simultaneously with the cross-sections above water level.

A.5 - Aerial photography

It must be made yearly, in early spring, simultaneously, as much as possible, with the surveys and cross-sections referred to above. The aerial photography must be submitted to photogrammetric treatment, with the scope of obtaining breakwater plans to a scale not below 1:500.

A.6 - **Underwater TV**

If the observations referred to above show any local damages in the submerged part of the breakwaters, video--records of these damages must be obtained.

B - Extraordinary observations

B.1 - **Overtoppings**

When overtoppings occur, they must be observed.

B.2 - **Just after a storm with Hs exceeding 5 m in deep waters**

A visual observation of the A.1 type must be carried out; if this observation advises it, observations of the A.2 type must be carried out too.

B.3 - **After a storm with Hs exceeding 8 m in deep waters**

Besides the visual observation referred to in B.2, just after the storm, a complete observation using all the techniques referred to in A must be carried out as quick as possible; the distances between cross-sections of the emergent and submerged zones must be reduced to 30 m (or even less, locally, if it is necessary to a better characterization of the damages).

Obviously, after every big repair of the breakwaters, a complete observation of type A must be done (identical to the one carried out regularly in April). This observation may be eventually restricted to the repaired zone.

Besides the observation of the structures themselves referred to above, the actions on them - waves, tides, currents and winds, must obviously be regularly recorded. However it is not the scope of this paper to consider in detail these observations.

First Results

- **Wave Records**

At Sines there are two Datawell directional wave recorders, one of which in deep water [CD (-100 m)]. The wave recording program is being done since 1973, with some gaps due to wave buoy problems. Data are available in real time.

- **Breakwaters Monitoring**

Construction profiles of the underlayers and the armor are available. The results of the usual construction material tests are also in Administração do Porto de Sines files.

There are some profiles collected since 1980 on a non-regular basis of Type C zone of West Breakwater.

Included in the Systematic Monitoring Program, APS has done some work, consisting of:

- Several visual observations;
- Photographic reports;
- Topographic observation of selected points in the superstructures;
- An aerial photography and a photogrammetric restitution of the part of the West Breakwater above sea level.

APS monitoring program is included in a proposal to EC Marine Science and Technology Program (MAST II), in which obtained data will be compared with data collected at Zeebrugge harbor using the same techniques and also with the equipment installed at its northwest breakwater (which comprises the measurement of wave characteristics, tidal currents and orbital velocities, water levels and water pressure fluctuations at several points in front of the breakwater, in the armor layer and in the core, air pressures in the core, impact pressures on the faces of armor units and video observations of uprush and downrush).

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