VENICE HIGH WATER BARRIERS
PROBLEMS ANALYSIS AND DESIGN APPROACH

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1. Introduction

In the last twenty years, several projects aimed to the solution of periodic flooding of large territories due to storm surge tides have been developed.

The Schelde and the Thames barriers have been successfully carried out.

The Venice problem is less urgent than the previous situations due to the total absence of casualties during all floods; however it appears more complex due to the city and surrounding environment that are extremely fragile, the presence of the port activity and the hazard of perturbation of the physical, chemical, biological equilibrium of the Venice lagoon.

The mobile barriers are one of the components of a complex system that is being projected.

The choice of the type of mobile barrier has been the result of a long process, with many breaks and restarts according to the occurrences of high tides and floods.
At the end, on Christmas 1980, a high tide reached 1.50 m on the m.s.l and the Government was forced to appoint a Committee in order to work out a final project.

2. Requirements and constraints imposed to the barrier from the Government Commission.

In the final report of the Feasibility Study and Preliminary Project edited by the Committee, the requirements or design criteria have been listed as follows:

a) the barrier should not require any pier in order to let the mouths width unchanged and to avoids obstacles and danger to navigation;

b) the barrier should not require any horizontal structure in order to avoid limits to the height of the vessels and aesthetic perturbation;

c) no rails fixed to the submerged foundation can be present due to maintenance and duration problems;

d) the closing and opening procedures have to be simple and fast;

e) complex and expensive foundation works have to be avoided;

f) the barrier has to be durable;

g) operation has to be extremely reliable;

h) maintenance have to be carried out easily and for single segments;

i) the barrier must resist to the wave action and to reduce as much as possible the forces impressed to the foundations;

l) ships collision against a section of the barrier should not compromise the efficiency of the whole structure.

The comment is that the listed requirements seem to be the advantageous features of the choosen solution more than a well ordered design criteria set.
In addition, no economical constraint has been included.

Other design criteria for similar applications have been set up in a more logical way, where the external and internal requirements have been separated with no limitations to specific components as rails or type of foundations.

3. The buoyancy flap gates barrier

In spite of the absence of any previous experience on this type of barrier or similar, the buoyancy flap gates barrier was indicated by the Committee as the most suitable for the Venice problem.

The main reasons why this solution seemed so attractive, might be:

- external features

a) width of the barrier has no limits (no piers)

b) the barrier is totally invisible (barrier open);

- internal features

c) no mechanical actuators

d) a satisfactory behaviour under the waves action in the sense that the forces impressed to foundations should have been considerably small;

e) any problem (ship collision, for instance) with one of the gates does not reduce the efficiency of the barrier to dangerous levels.

Each gate was formed by four or five cylindrical modules (4.8 m diameter) as shown in fig.1.

The Committee Members had a very short time available in order to go through a complete feasibility study, so many problems related to the solution proposed remained open.

When the Consortium, to whom the Government committed the Project, started their work, the list of critical points was considerably long; the main points are the following:

- dynamic behaviour of the flap gates under wave action
- siltation of the recesses
- corrosion and fouling of the structures permanently under water
- inspection and maintenance of the barrier and their interference with the port activity
- foundations.

It can be affirmed that the main problems or critical points of this type of barrier, come from two features of the gate itself:

a) stability: the flap gate changes its position (inclination) according to the forces acting on the gate itself.
Two are the main effects: the first one is that the position of each gate has to be controlled and maintained by means of an automatic control system for each gate so the number of components needed for the whole barrier is considerably high and the control system is more complex in comparison with other type of barriers; the second consequence is the dynamic behaviour of the barrier under wave action, that resulted more complex and troublesome than the authors of the original project could imagine without experimental models.

b) extremely poor accessibility: the gates, when inoperative, rest in the foundation recesses on the channels bottom: this fact brings as main consequences that the movable parts of the system are exposed to the aggression of the underwater environment and, in addition, they are accessible with great difficulties for inspection and maintenance.

As far, the main part of the design work has been addressed to minimise the number of components permanently under water and to set up inspection and maintenance procedures compatible with ship navigation in the mouths.

Unfortunately, the fixed parts of the barrier, like the female connectors, the desiltation systems, the joints between the caissons etc. can be repaired or modified only with high costs and long underwater operation.

4. Problems analysis and developed solutions

In order to find the proper solution to every problem, a big organisation for research and development was set up.
Many national and foreign Laboratories have been called to cooperation.
The hydraulic research facilities in the University of Padua have been refurbished and adapted to the different aims.
A full scale gate test rig, named MOSE (MOdulo Sperimentale Elettromeccanico), has been put in operation in 1989.

4.1 Shape of the gate: tests of the different alternatives.

Designers examined two different alternatives to the original one (see fig.2):

a) flap gate shaped as a parallelepiped caisson (shortly named "rectangular flap gate")

b) the horizontal cylinder flap gate

The option a) has been considered instead of the original one since a simpler and less deep recess is needed, and the buoyancy force application point is the same as the original one.

The option b) was set up in order to move the buoyancy force as far as possible from the hinge: the air volumes to balance the hydrostatic forces due to the level differences are consequently smaller.

However, the tests on hydraulic scale models in the flume showed the worst behaviour under wave action, due to a big sub harmonic resonance, as it will be described later.

Furthermore, the recesses were considerably deeper and complex to build and more sensible to siltation.

At the end, the rectangular gate has been considered the most suitable type to be adopted.

As the inclination is concerned, the original configuration shows an inclination angle about 75 degrees instead of an inclination of 55 degrees in the chosen solution: as a matter of fact, the flume tests showed a better behaviour under wave motion.

Dimensions and weights of the gates of the four sections of the barrier are shown in the table at fig. 3.

4.2 Dynamic behaviour of the barrier under wave action

In the chosen type of barrier, each gate position depends on the balance between the hydrodynamical and hydrostatic forces acting on the gate and the buoyancy force due to the air volume.

This feature differs completely from the Schelde or Thames barriers schemes that are "rigid" since the position of the gates are uninfluenced by the forces acting on them.

The behaviour could be similar to the inflatable barrier's one, where some resonance phenomena occurred in the realty with disastrous consequences.

For these reasons a great attention was paid from the beginning to the dynamic behaviour of the barrier in the wave tests.

The early investigation were carried out in a flume, in order to check the best dynamic behaviour at different shapes, inclinations, masses, etc.

In a narrow range of regular wave periods each type of gate presented an unexpected way of oscillation, that is, in simple words, that each gate oscillates with a frequency equal to the forcing wave and with a frequency roughly half the wave frequency: moreover the movements of the gates are not simultaneous but a phase difference occurs between the flaps according to different "modes", mode 1, mode 2 and mode 3, as shown in fig. 4, that depend on the forcing wave period.

At an early stage, there was the suspect that this behaviour was due to the presence of the walls (tests in a flume), but a later model with half wide gates showed and confirmed the presence of the gate resonance, at any wave period.

Before evaluating the problems arising from this behaviour, as the flows through the openings between the flaps, the amplitude of oscillations up to flapping over of the gates, the forces impressed to the hinges (foundations), researches had been carried out in order to achieve the following objectives:

a) a convincing explanation of this behaviour;

b) a mathematical model in order to have a tool available for the final design;

c) investigation on the possibility to reduce the phenomena;

d) evaluation of the consequences on the full scale barrier in the real conditions (irregular waves) and influence of the phenomenon on the barrier feasibility;

e) evaluation of the influence on the resonance phenomena of the angle of incidence of the wave front.

By means of a mathematical model and of three different physical models, 2D and 3D, the following conclusions could be reached:

- with a simplified mathematical model it can be deducted that the possibility of a sub harmonic response is in the equations describing the gate motion;

- resonance occurs when the wave period is nearly half the natural oscillation period of the gates in the different modes; the phenomenon is strictly linked to the added mass and radiation: sketches of fig. 5 show how at low wave frequency far gates can get interaction;

- flow through the gap between the gates, and the shape of the edges of the gate have very small influence on the resonance phenomenon;

- resonance is stronger at higher inclination angles;

- water level difference across the gates has small influence on resonance;

- resonance occurs also at irregular wave conditions, but this resonance is of an irregular nature;
  the peak of oscillation amplitudes and forces on the foundations are substantially equal to those recorded with regular waves;

- increases of water leakage between the gates due to the resonance phenomena are small and have a negligible influence on the barrier efficiency.

4.3 Siltation of the recesses

As the flaps are raised and come out of the recesses an equivalent volume (over 2000 cubic meters per gate) of the surrounding water takes place into the recesses.

A considerable amount of solids as sand and debris are transported by the entering streams and get trapped in the recesses.

A solid transport and settlement in the recesses can occur during the closing operation of the barrier due to the sequential raising of the gates.

If a gate fails in raising, the level in the lagoon can be held under the safeguard limits, but an high velocity flow over the unoperative gate can transport solids and debris that can grow the siltation process in the other gates recesses.

In addition, solids can drop and settle during gates operation.

As siltation prevent gates to be fully contained into the recesses, problem for the ship navigation may occurr toghether with dangerous stresses on the hinges, mainly since the dropping velocity of the gates into the recesses cannot be controlled.

BHRA laboratory has been appointed to study a suitable system to remove the solids from the gates recesses.
They shaped the recesses in several hoppers in order to collect the solids and eject them by means of hydraulic jet pumps.

According to the tests carried out on the model scaled 1:10 and on the MOSE, solids up to 60 mm equivalent diameter can be removed by the proposed system.
Some trouble may arise with not-free-flowing materials as

algae or plastic films or similar.

In addition, the system (jet pumps and pipes) is embedded in the concrete foundations and therefore their maintenance has to be carried out by underwater staff and equipments.

4.4 Fouling due to vegetable and animal growing.

It is expected that the external surfaces of the gates shall be considerably fouled by animal growing.
Fouling can be prevented by paints but, due to the risks of pollution of the surrounding water, this technology can be used just for very small surfaces.

As a consequence, fouling have to be removed by means of brushes or similar tools.

There is no doubt that this kind of operations are very uncomfortable and shall be a cost and a problem for ship navigation.

On the other side the problems coming from an excess of fouling are not yet well evaluated by the designers, so it may be that fouling has no influence on the gates efficiency: the first period of barrier operation will give indication how to cope with fouling.

4.5 Corrosion of the steel structures

Corrosion of the submerged steel structures will be prevented by means of active and passive systems widely adopted in similar cases.

Pipes for air injection and suction and silt removal piping can't be internally protected, so not corrodible materials as stainless steel with high molybdenum content or copper alloys, have to be used.

4.6 Inspection and maintenance

As previously underlined, the type of barrier, together with the advantages considered, has the big drawback that the gates can be accessed with great difficulties.

It is unthinkable to carry out overhaul in situ, so the gates have to be removed and spare units have to be provided.

Gate replacement at time intervals (a provision of five years has been stated at the time being) imposes a lot of special requirements in the design of the gates.

First of all the most of the parts and components (i.e. hinges, piping systems, sensors, etc) should be removed together with the gate: two types of special plug-in connectors between gates and foundation have been tested on the MOSE.

The first one came from the underwater oil piping system, but some problem arose during tests, so the preference went to a specifically designed connector shown in fig.6.

Two lines for air immission and extraction are provided, one on duty and one for backup.

The inclination can be measured by a mechanical shaft passing through the connector or by means of an electronic sensor installed on the gate and connected by wire to the controller through the main connector.

The female of the connector has to be steadily fixed to the foundation and if it is damaged by an over stress (ship collision as an example) its overhaul in situ can be a very serious problem.

Means to prevent damage to the connectors have been examined by the designers but none of them has been approved so far.

Assumed that the gate can be disconnected from the foundations without any assistance of underwater operators, it has to be raised and the spare modulus has to be installed on the foundations, possibly without need of divers as well.

The crucial point is the time needed for the operation in order to minimise navigation breaks.
In addition, frequency of closure of the barrier is foreseen to increase in the future due to the raising of the sea level.
The time intervals available for maintenance operation will decrease consequently, so the replacement procedure has to be as fast as possible.

The initial choice of a jack-up pontoon has been abandoned due to the long positioning operations.

The designer staff suggested the use of a gantry crane that can be moved on rails on the foundation (see fig. 7)

According to this indication, the gantry crane moves from one end of the barrier, takes position overhead the gate that has to be replaced, lowers a frame with four locks that enter the relevant recesses on the gate, and finally lift the gate out of water and put it on a pontoon.

The procedure can be carried out only in predefined conditions of waves motion and stream velocity, due to the dynamic effects of the said parameters on the gate and consequently on the gantry crane itself.

If the value of wave height and water speed exceed the limits during the operation, the gate has to be lowered and the replacement mission has to be abandoned.

Sediments can play a crucial influence on the operation: a cleaning system has been provided to remove the sediments inside the female of the connectors and an equipment to check if the cleaning action was successful has to be provided.

Four similar cleaning systems have been foreseen in order to ensure guarantee the entrance of the twist locks in the relevant recesses.
The checking procedure is similar to the connector's one.

According to the designers provisions,(diagram in fig. 8) the replacement of one gate requires 8 hours.

Together with siltation, inspection and maintenance are the most critical points of the solution.

5. Reliability: risks identification and analysis

In order to give a comprehensive picture of the major hazards and of their connection to the related causes, a risk tree has been proposed, as shown in fig. 9.

A risk analysis has been carried out by an international Committee appointed by the Consortium of the technical appraisal of the reliability of the electrical and mechanical equipment and control system.
Adequacy and reliability of the maintenance methods and procedures have been checked as well.

The risk tree shown in fig. 9 is substantially the same of the final report of the International Committee, except for the area concerning the "Insulae" and some relations between ship navigation and gate maintenance, that have been underlined.

As written in the said report, the event "Venice flooded" means that water level exceeds 1.30 m at Punta della Salute: it can occur as a consequence of a failure of one or two gates during a very high level and long duration storm, or as a consequence of a medium high tide, not considerably long, but with a high number of gates out of service.

This example has been done in order to highlight that the term "Movable barrier not effective" has to be defined with caution, considering also level and duration of the storms.

Five class of reasons why the movable barriers can be not effective have been identified.

They are:

- Unacceptable water leakage across the raised barrier

  That means that the barrier's design specification are not met or the design criteria are not adequate.

- Barrier not raised

  The barrier is not operated: this can be caused by a not availability of the barrier or by a failure of the starting operation.

- Part of the barrier missing

  The barrier is operated but the level and the duration of the storm are incompatible with the fact that some gates are missing for any reason.

- Barrier fails to rise

  The barrier is operated but part of it can't be raised or can't reach and maintain the needed height.

- Barrier fails under load.

  Barrier is operated, no problem at the beginning, then a failure in one or more gates occurs.

At the time being, many failure probabilities are not yet determined, due to the problems previously exposed..

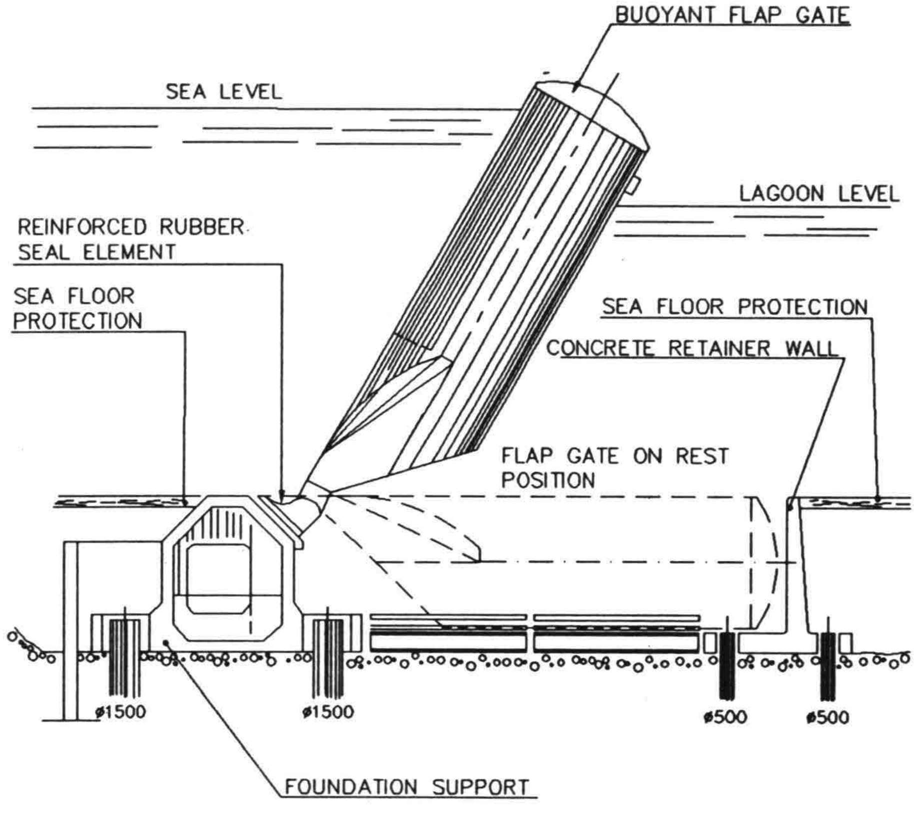

BUOYANT FLAP GATE
SEA LEVEL
LAGOON LEVEL
REINFORCED RUBBER SEAL ELEMENT
SEA FLOOR PROTECTION
SEA FLOOR PROTECTION
CONCRETE RETAINER WALL
FLAP GATE ON REST POSITION
ø1500
ø1500
ø500
ø500
FOUNDATION SUPPORT

FIG. 1

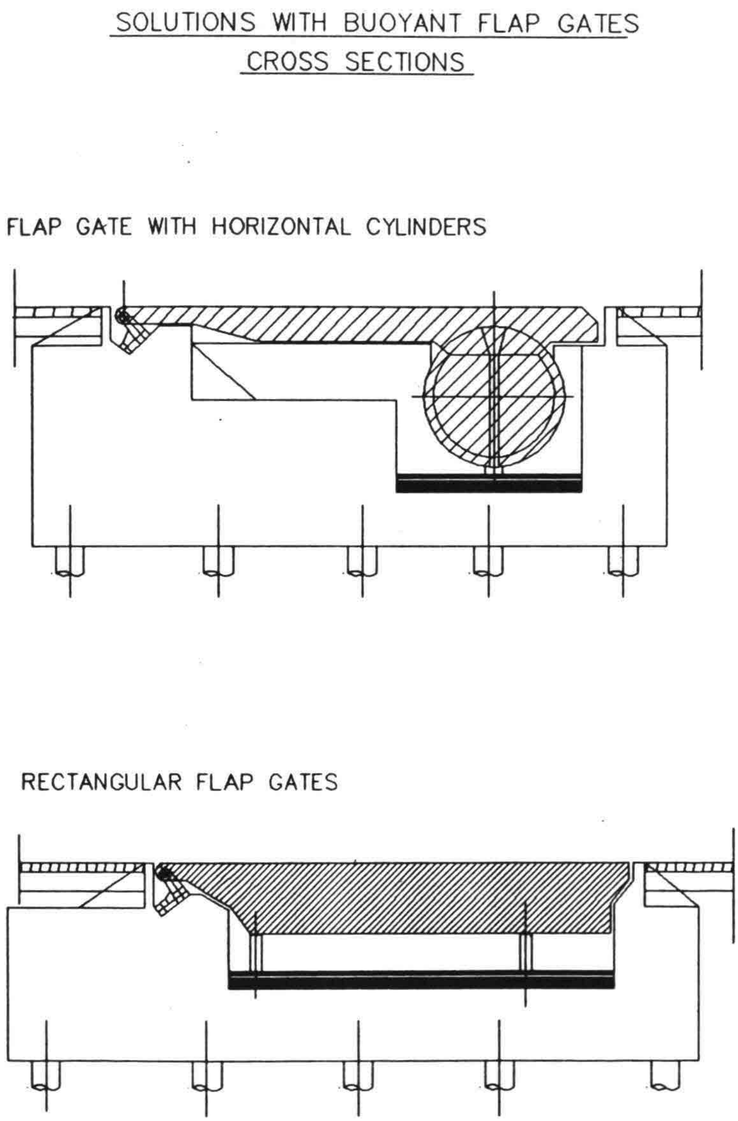

SOLUTIONS WITH BUOYANT FLAP GATES
CROSS SECTIONS
FLAP GATE WITH HORIZONTAL CYLINDERS
RECTANGULAR FLAP GATES

FIG. 2

BARRIER MAIN FIGURES

	MOUTH DEPTH (m)	MOUTH WIDTH (m)	GATES NUMBER	GATES WIDTH (m)	GATES LENGHT (m)	GATES HEIGHT (m)	GATES WEIGHT (t)
MALAMOCCO	15	400	20	20	28.0	4.0	460
SAN NICOLO'	11	400	20	20	21.5	4.0	330
CHIOGGIA	10	360	18	20	20.5	4.0	310
TREPORTI	6	420	21	20	18.5	3.8	270

FIG. 3

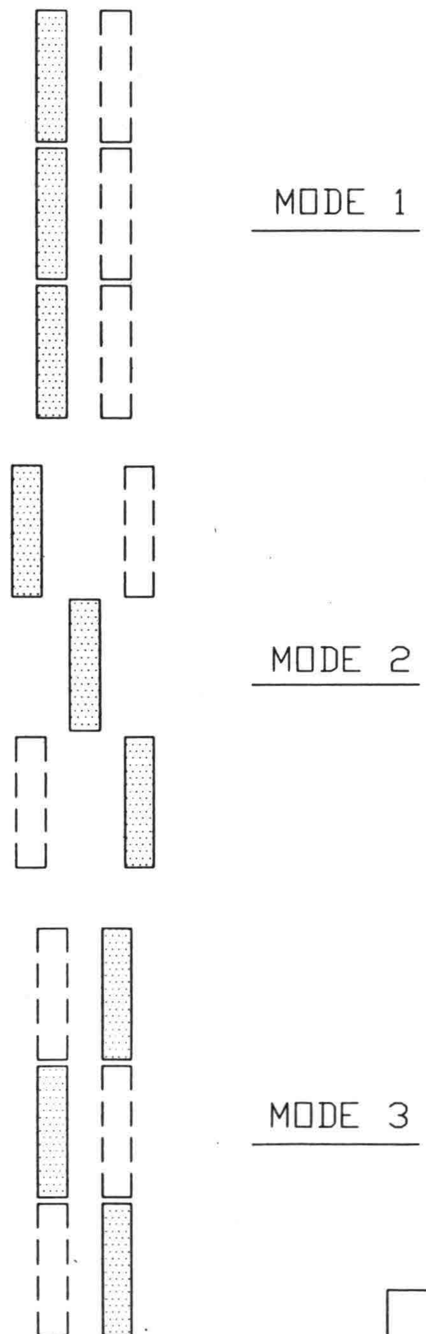


FIG. 4

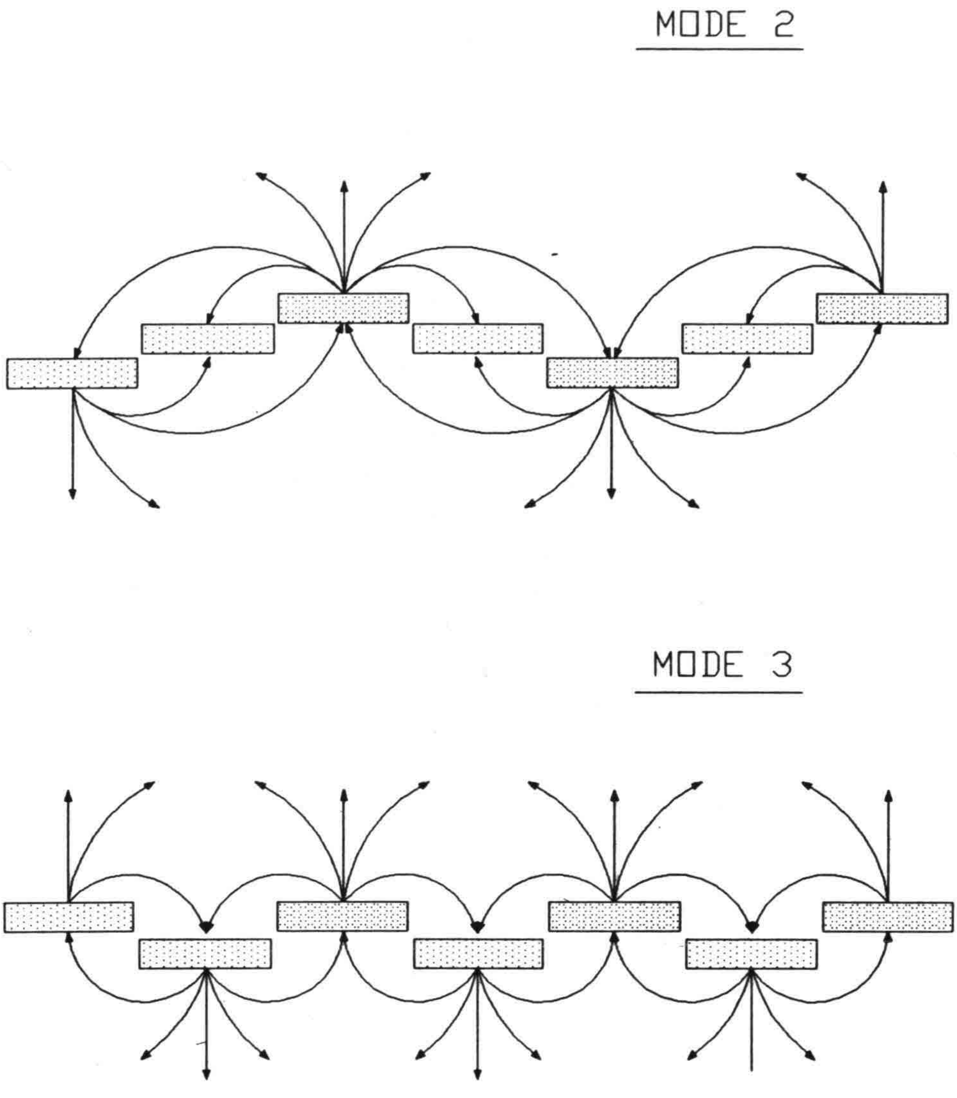
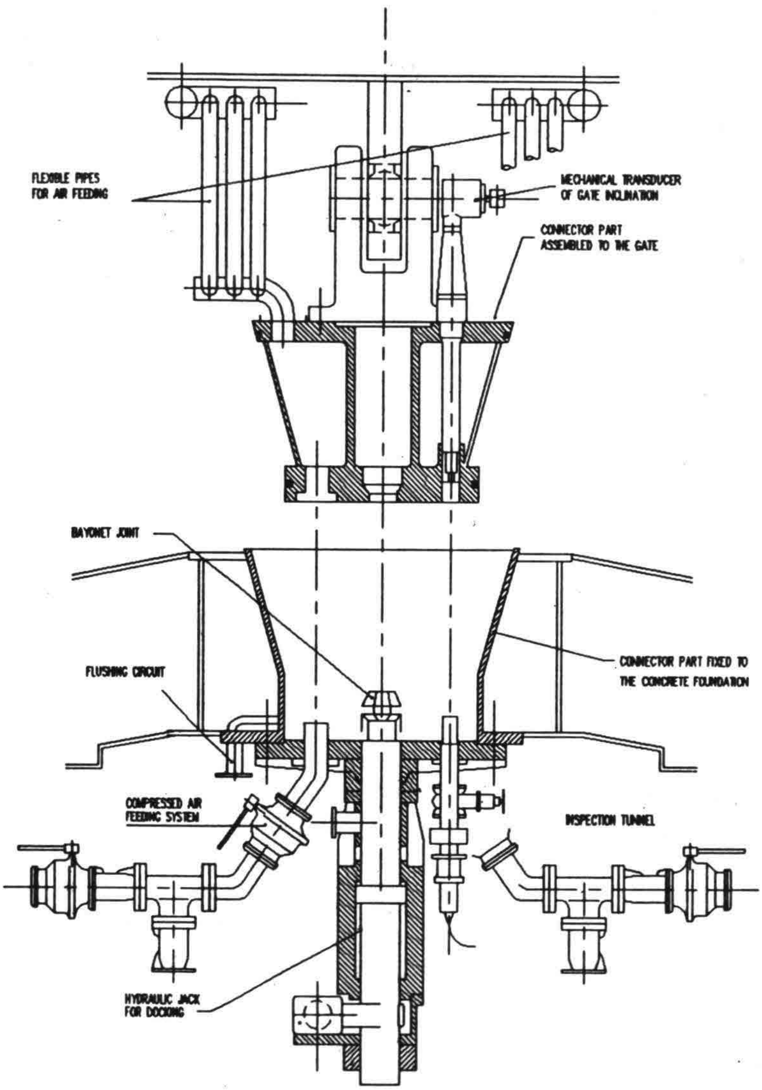


FIG. 5



CONNECTOR – HINGE

FIG. 6

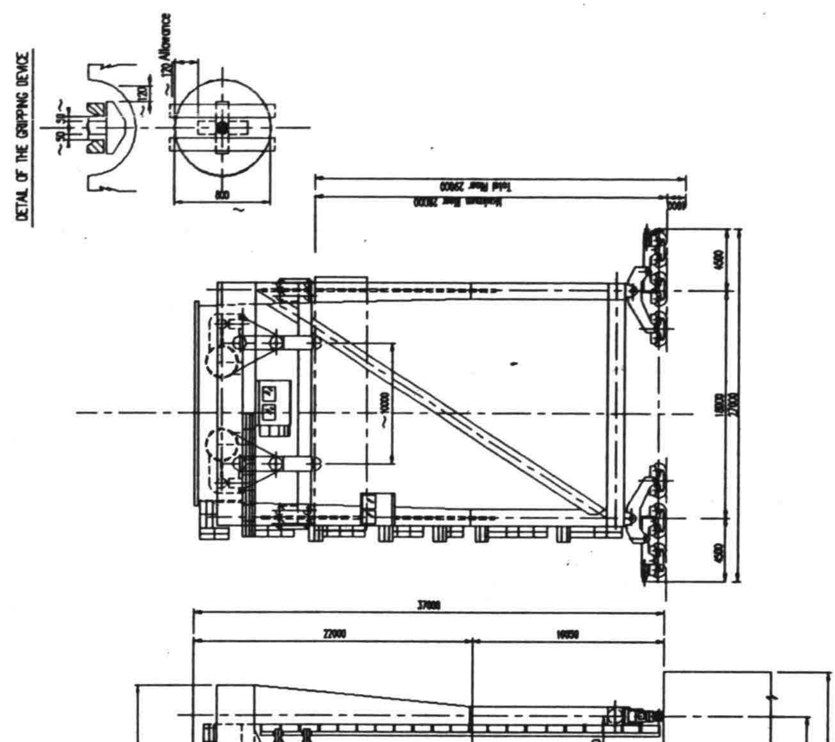

DETAIL OF THE GRIPPING DEVICE
~120 Allowance
GRANTY-CRANE FOR THE MAINTENANCE OF THE FLAP GATES
CAPACITY 900 Tons (Malamocco)
SEA LEVEL
GRIPPING DEVICE OF THE FLAP GATE
SEE DETAIL
37000
22000

FIG. 7

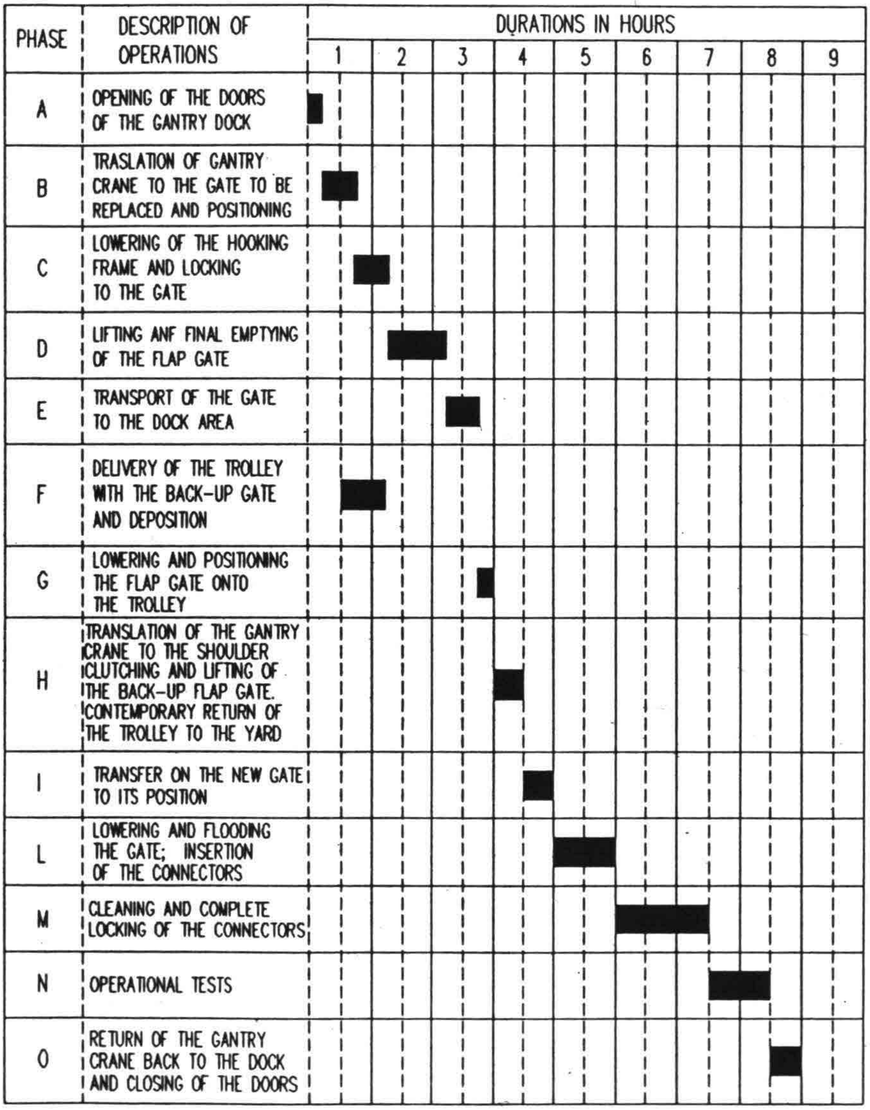

PHASE
DESCRIPTION OF OPERATIONS
DURATIONS IN HOURS
1 2 3 4 5 6 7 8 9
A
OPENING OF THE DOORS OF THE GANTRY DOCK
B
TRASLATION OF GANTRY CRANE TO THE GATE TO BE REPLACED AND POSITIONING
C
LOWERING OF THE HOOKING FRAME AND LOCKING TO THE GATE
D
LIFTING ANF FINAL EMPTYING OF THE FLAP GATE
E
TRANSPORT OF THE GATE TO THE DOCK AREA
F
DELIVERY OF THE TROLLEY WITH THE BACK-UP GATE AND DEPOSITION
G
LOWERING AND POSITIONING THE FLAP GATE ONTO THE TROLLEY
H
TRANSLATION OF THE GANTRY CRANE TO THE SHOULDER CLUTCHING AND LIFTING OF THE BACK-UP FLAP GATE. CONTEMPORARY RETURN OF THE TROLLEY TO THE YARD
I
TRANSFER ON THE NEW GATE TO ITS POSITION
L
LOWERING AND FLOODING THE GATE; INSERTION OF THE CONNECTORS
M
CLEANING AND COMPLETE LOCKING OF THE CONNECTORS
N
OPERATIONAL TESTS
O
RETURN OF THE GANTRY CRANE BACK TO THE DOCK AND CLOSING OF THE DOORS

FIG. 8

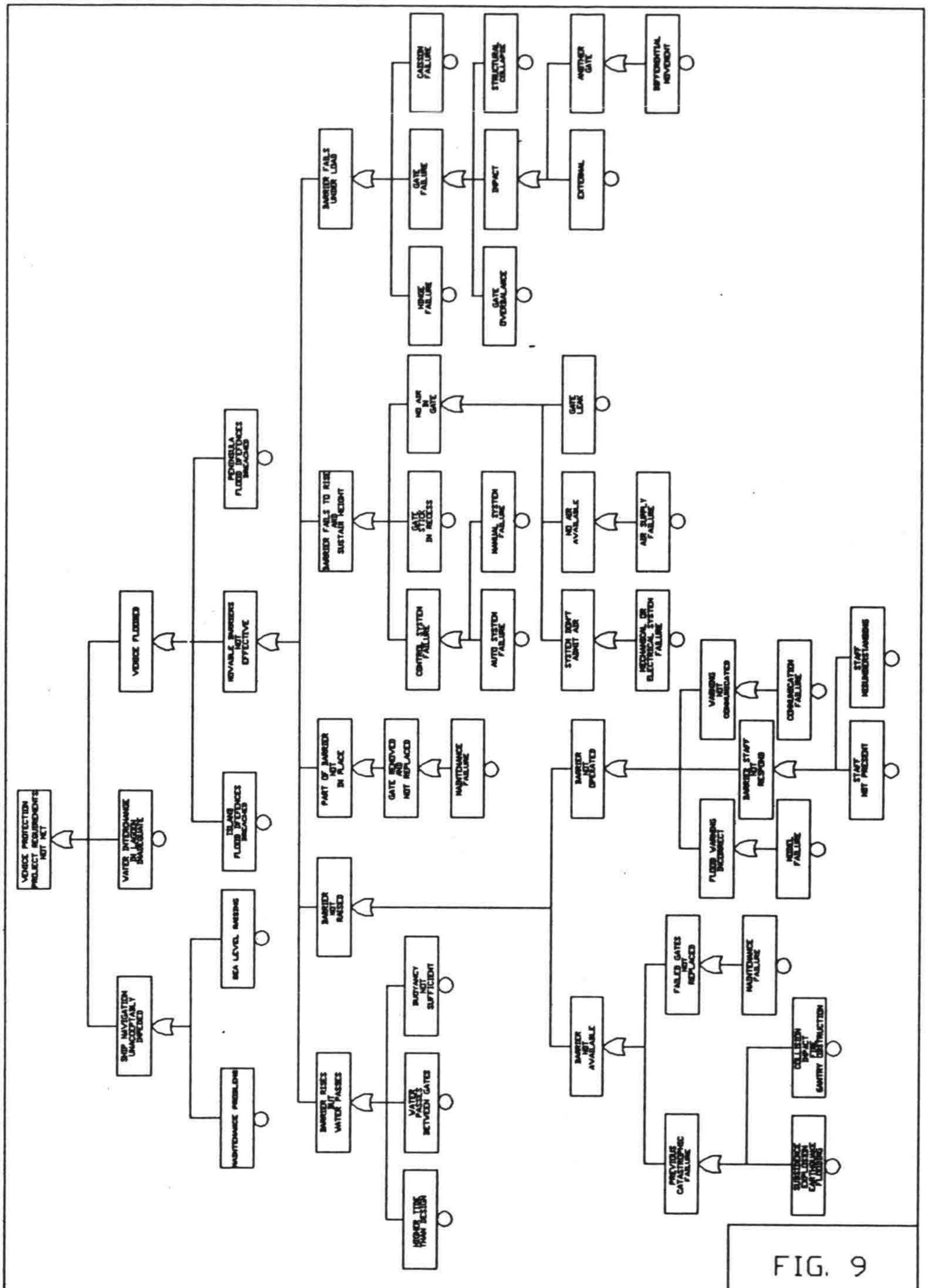

VENICE PROTECTION PROJECT REQUIREMENTS NOT MET
SHIP NAVIGATION UNACCEPTABLY IMPEDED
WATER INTERCHANGE IN LAGOON INADEQUATE
VENICE FLOODED
MAINTENANCE PROBLEMS
SEA LEVEL RAISING
ISLAND FLOOD DEFENCES BREACHED
MOVABLE BARRIERS NOT EFFECTIVE
PENINSULA FLOOD DEFENCES BREACHED
BARRIER RISES BUT WATER PASSES
BARRIER NOT RAISED
PART OF BARRIER NOT IN PLACE
BARRIER FAILS TO RISE AND SUSTAIN HEIGHT
BARRIER FAILS UNDER LOAD
HIGHER TIDE THAN DESIGN
WATER PASSES BETWEEN GATES
BUOYANCY NOT SUFFICIENT
GATE REMOVED AND NOT REPLACED
MAINTENANCE FAILURE
CONTROL SYSTEM FAILURE
GATE STUCK IN RECESS
NO AIR IN GATE
HINGE FAILURE
GATE FAILURE
CAISSON FAILURE
AUTO SYSTEM FAILURE
MANUAL SYSTEM FAILURE
GATE OVERBALANCE
IMPACT
STRUCTURAL COLLAPSE
SYSTEM DON'T ADMIT AIR
NO AIR AVAILABLE
GATE LEAK
EXTERNAL
ANOTHER GATE
MECHANICAL OR ELECTRICAL SYSTEM FAILURE
AIR SUPPLY FAILURE
DIFFERENTIAL MOVEMENT
BARRIER NOT AVAILABLE
BARRIER NOT OPERATED
PREVIOUS CATASTROPHIC FAILURE
FAILED GATES NOT REPLACED
FLOOD WARNING INCORRECT
BARRIER STAFF NOT RESPOND
WARNING NOT COMMUNICATED
MAINTENANCE FAILURE
MODEL FAILURE
COMMUNICATION FAILURE
SUBSIDENCE EXPLOSION EARTHQUAKE FLOODING
COLLISION IMPACT FIRE GANTRY DESTRUCTION
STAFF NOT PRESENT
STAFF MISUNDERSTANDING

FIG. 9

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