CHAPTER 152

THE STRUCTURAL RESPONSES OF DOLOS ARMOR UNITS UNDER THE DYNAMIC LOADING

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ABSTRACT

The "Dolos" is now used widely for harbor and shore protection works in various ports of Taiwan (R.O.C.) and some damage has been noted. The purpose of this research is to understand the major factors which influence dolos breakage. The factors studied include plain or reinforced concrete, rebar arrangement, chamfered or enlarged fillet corner and the fracture behavior by pendulum and drop test.

Site observations and laboratory dynamic tests are included in this paper. The site observation investigated the behavior of the broken dolos at each habor. In the laboratory dynamic tests 42 specimens of 1.5 tons dolos were used for drop tests; frontal and transverse pendulum tests (Fig.1).

The results show that the fracture behavior in the laboratory tests agree with those of site observation, i.e. cracking due to frontal impact is more severe than that of transverse impact. The arrangement of rebar also influences the strength of the dolos. Therefore, it is suggested that the dynamic tests are necessary for dolos tesing.

INTRODUCTION

The sequence of breakwater failures in the late seventies and early eighties raised questions whether there were deficiencies in the design or construction of rubble mound breakwaters. Conclusions from some of the damage investigations were (1):

- Damage to dolos of more than 15 tons can occur due to rocking, and hydraulic damage criteria are no longer applicable.
- More basic research and full scale monitoring is required to establish proper design guidelines.

A successful desing must ensure both the hydraulic and structural stability of the units. Consequently, problems related to the structural strength of dolos have been discussed. Lillevang(2) used 3D

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photoelastic stress analysis to examine the stress distribution of dolos models with various shapes of stem-fluke corner under static loads. Burcharth(3) did drop and pendulum tests using 1.5 tons and 5.4 tons dolos, and proposed a method for a dynamic test, and Terao(4) also carried out drop and static load tests using 0.04 tons, 0.4 tons and 4 tons units.

Dolos have been used in various ports of Taiwan, R.O.C. The dolos have suffered impact loading resulting from rocking/rolling of units and missiles of broken units.

SITE OBSERVATIONS

Fig.2 is key map of the site obscration of dolos destruction in Taiwan and Table 1 shows a summary of detailed information of these dolos projects in Taiwan. The most severe storm damage which occurred at the east breakwater of Hua-Lien Harbor during typhoon Andy was up to 70%. The probable reason was the limited ability for placing 40 tons Dolos, hence the units were unstable on the steep armor slope. Damage of 20% occurred at the west breakwater of Hua-Lien Harbor, while still under construction and before the crown wall had been constructed. Hua-Lien Harbor faces the Pacific ocean and the units suffered from severe wave impact loade. Typical dolos destruction in Taiwan, R.O.C. is shown in Fig. 3.

THEORETICAL CONSIDERATIONS FOR ANALYSIS OF DYNANMIC TESTS

The dynamic testing of dolos to destruction is to simulate the impace force when the units are rocking or struck by broken units. Burcharth (3) derived formulae for the maximum tensile stress in a dolos exposed to impace load in a drop test and a pendulum test (Fig.4) by using impulse moment equations and dimensional analysis as follows:

$$\text{drop test : } \frac{\sigma}{MghC^{-3}} = C_1 \frac{1+r}{r^2}\sqrt{\frac{E}{\rho gh}} \quad , \quad 0.3 \leqq 4 \leqq 0.4 \quad \ldots\ldots\ldots\ldots \quad (1)$$

$$\text{pendulum test (1) : } \frac{\sigma}{mghC^{-3}} = C_2 \frac{1}{r^3}\sqrt{\frac{E}{\rho gh}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where σ = maximu tensile stress
$M(m)$ = dolos (pendulum) mass
h = fall height of pendulum (or dolos center of gravity)
C = dolos height
g = gravitational acceleration
E = elastic modulus
ρ : mass density of pendulum and dolos
r : waist ratio (0.319 in this test for 1.5 tons dolos)
C_1 and C_2: constant factors to be determined by tests

Since thest formulae were developed for specific test set-ups involving bending and shear stress in the most exposed cross seciton, we developed another test set-up for a transverse pendulum test which creates mainly torque in the stem. A formula were developed similar to the frontal pendulum test as follows:

pendulum test (2) : $\frac{\tau}{mghC^{-3}} = C_3 \frac{1}{r^3}\sqrt{\frac{E}{\rho g h}}$ .... (3)

where τ = torsion
C_3= constant to be determined by tests.

DROP TEST PENDULUM TEST(1) PENDULUM TEST(2)

Fig.1 DYNAMIC TESTING SET UP

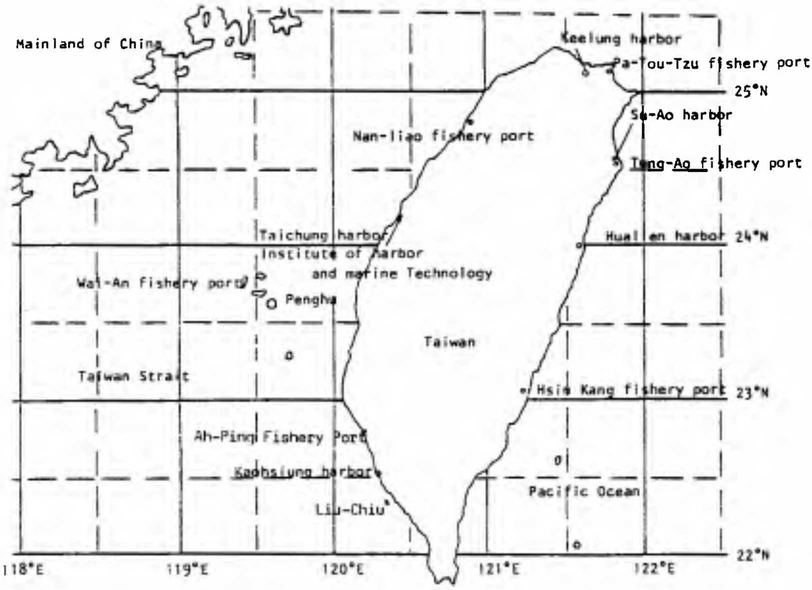


Fig. 2 KEY MAP OF THE SITE OBSERVATIONS OF DOLOS DESTRUCTIOIN IN TAIWAN

KEELUNG HARBOR

SU-AO HARBOR

HALIEN HARBOR

PA-TOU-TZU
FISHING PORT

SU-AO HARBOR

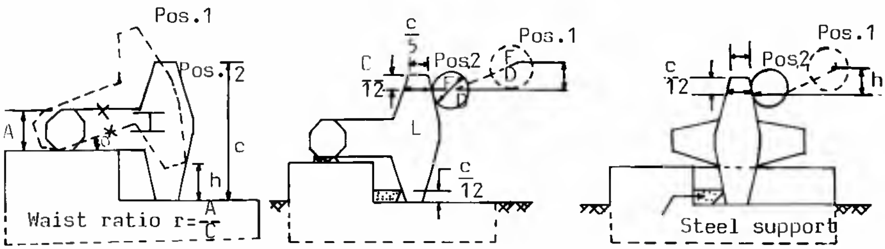
HALIEN HARBOR

KAOHSIUNG HARBOR

TUNG-AO FISHING PORT

HSIN KANG FISHING PORT

Fig. 3 TYPICAL DOLOS DESTRUCTION IN TAIWAN



(a) Drop Test (b) Pendulum Test (1) (c) Pendulum Test (2)

Fig 4. SIMULATED DYNAMIC TEST

TABLE 1: SUMMARY OF DETAILED INFORMATION ON-KNOWN DOLOS PROJECTS IN TAIWAN

Project & details		Design conditions					Structure geometry				Dolos armouring particulars							Site Experience										
Name and period of construction	part *	wave height H (m)	wave period T (s)	Angle approach (°)	Recurrence (years)	Design damage (%)	Armour slope (tanα)	Crest heitht of Dolos(m)	Armour depth (m) ±	Water depth (m)	Dolos mass W(tons)	Dolos height (m)	Waist ratio (-)	Density of block tons/m3	Design comper strength (Mpa)	Packing density	Under-layer mass (tons)	Dolos stripping (days) x	Dolos moving (days)	Dolos placing (days)	28days compr strength (Mpa)	Breakage of Dolose (%) during: Manufacture	placing	Initial Shake down	Storm wave height (m)	Storm damage (%)	Number of dolos used	Unit cost (US$)
Su - Ao harbour																												
composite caisson breakwater 1974-1979	MBT	10	11		13		0.5	+32	25	25	30	4.3	0.32	2.45	28		2-5	1	5	28	28						5130	1000
Rubble mound breakwater 1974-1979	MBT	10	13		13		0.5	+27	8-20	8-20	10	3	0.32	2.45	28		2-5	1	5	28	28		3.92	0.27			9300	300
Keelung Harbour																												
pa-chyy-Men breakwater 1979-1980	MBT						0.33 / 0.5	+11.8 / +14.1	-5.0 / -10.0	-6.0 / -11.0	20 30 40 40	3.76 4.31 4.79 4.79	0.27 0.26 0.26 0.26	2.35	35 24.5 35 24.5	2	3-5 0.5-1 0.5-1 0.5-1	3	7	15	35 24.5 35 24.5	0.3	0.2	0	8-9	0	1320 1093 698 1193	443 747 1076 985
East Breakwater 1976-1981	MBT						0.67	+7.0		Sea side -2 - -12 harbor +3 - -24	15 20	3.43 3.76	0.27 0.27	2.5 2.35	35 35	2	0.5-1 0.5-1	3	7	15	35	0.3	0.2	0	8-9	0	1962 1383	193 300
Kaohsiung harbour																												
Second harbor breakwater 1977-1984	MBT	6.0	10							13.0	7.5	2.67			20.59			2	7		23.6						3025	200
An-ping breakwater 1977-1978	MBT	6.0	10							8.0	7.5	2.67			20.59			2	7		23.6						5023	200
Chung Shan university breakwater 1983-1984	SP									6.0	7.5	2.67			24			2	7		27.6						3280	200
Hualien harbour																												
Old- east breakwater 1980-1982	MBT						2	+11	8 6	6 6	4 4	4.66 4.66	0.33 0.33	2.4 2.4	28 28	1.49 1.49	>5 NO	3	7	28	30	0	0	1	13.0# (calc)	70§	404	1100
Old- east breakwater 1983-1984	MBT						2	+13	6	6	41 40	4.66 4.66	0.33 0.33	2.4 2.3	28 28	1.49 1.49	NO NO	3	7	28	30	0	0	1			16 465	1100 850
New- west breakwater 1980-1983	MBT	9	12.3	27	25	1	0.5	+16	6.5	6.5	20	3.76	0.34	2.3	28	1.25	3-5	3	7	28	30	0	0	0.5	13.0# (calc)	20§	2835	450
New- west breakwater 1980-1983	MBT MBH	9	12.3	27 63	25	1	0.5	+16.5-+18.5 +12	7-9	7-9	20	3.76	0.34	2.3	28	1.25	3-5	3	7	28	30	0	0	1			591	450
Fishery Ports:																												
Pa - Tou - Tzu 1980-1982	MBT	7.7-13.0	11.8-13.1	0 12		1	0.5	+2.7	-11	-20	30	4.32	0.32	2.4	20.7	0.76	7										3000	1050
Nan - liao 1982-1984	MBTIS MBT MBH	3.7 / 1.8	9.3 / 9.7	5 / 45		1	0.67 0.5	+4.3 +4.5	-2.0 -4	-3.5 / -5.5	4 5	2.5	0.3	2.4	17.2	0.71 0.7	0.2 0.5										3434 6165	120 150
Liu - Chiu 1984	MBT MBH	7	11.7	0		1	0.5	+0 +0.32	-3 -4	-8	10 30	2.99 4.32	0.33 0.33	2.4 2.4	17.2 17.2	0.74 0.74	2 4	2	7	28							450 270	320 900
Hsin - Kang 1978	MBH						0.5	+1.1	-9.5	-9.5	7.5				17.2												428	
Wai - An 1982	MBT	4.1	8.6				0.67	+6.5	-3.5	-3.5	5 10				17.2 17.2												402 1525	
Tung - Ao 1983	MBT										12																100	

* MBT/MBH -Main breakwater Trunk/Head; SP-Shore protection: MBTIS-MBT inner slope.

x All days after casting.

± All depths are to be mean sea level (MSL).

\# Calculated from Andy Typhoon. (July 28 1982).

§ Damage occured at the section of MBT where crown wall had not built completed: Two Thirds of the damage was caused by Andy Typhoon.

TEST PROGRAMME

Test Specimens

A total of 42 units of 1.5 tons dolos were used in the tests and classified into seven types. Six units of each type were used for drop tests, frontal and transverse pendulum tests. The geometry and specifications of the units are shown in Fig. 5 and Table 2 respectively.

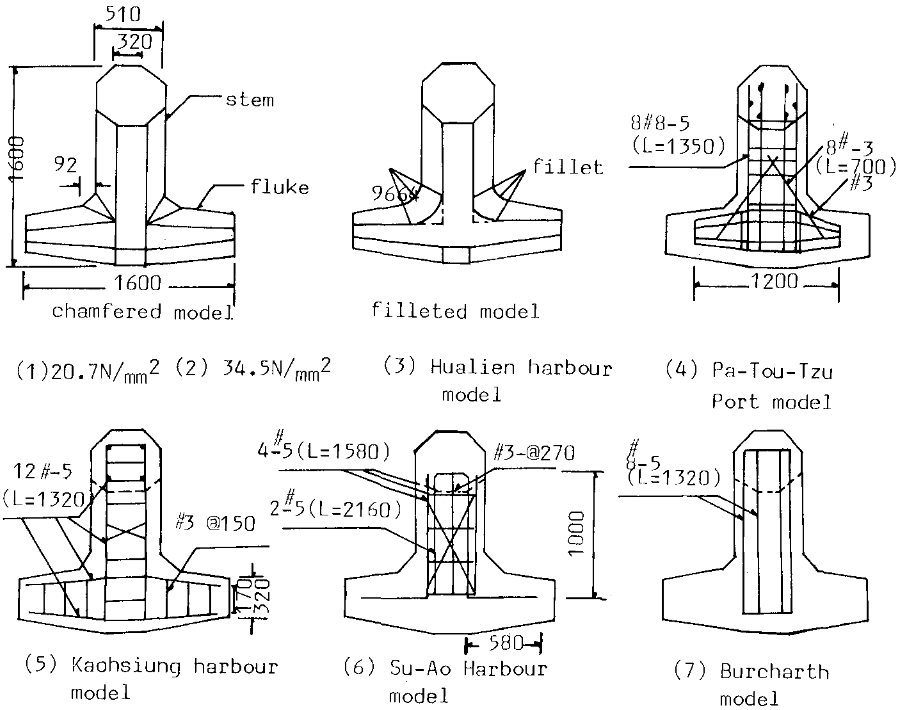


Fig 5. GEOMETRY OF DOLOS UNITS

Fig. 6 shows the preparation of dolos specimens. For quality control, two control specimen (15 cm x 30 cm) for each dolos unit were manufactured and tested by 100 tons universival material testing machine (Fig.7). They were also taken nondestructive tests by using test hammer (Fig.8) and ultra-sonic pulse measuring units (Fig.9). These data were compared to the compressive strength of control specimen's results.

TABLE 2. SPECIFICATIONS OF THE TEST SERIES

Series No.	1	2	3	4	5	6	7
Design compression strength (N/mm2)	20.7 ——			34.5 ——			
Mass of unit M(Tons)	1.39	1.44	1.44	1.49	1.48	1.47	1.46
Density ρ (Tons/ m^3)	2.14 ——			2.22 ——			
Height of unit C (mm)	1600	1600	1600	1610	1610	1600	1600
Waist ratio $r=\frac{A}{C}$	0.319 ——			0.329 ——			
Mass of pendulum m(Tons)	0.318 ——			0.323 ——			
Cement content (kg/m3)	294 ——			417 ——			
Water-Cement ratio	0.68 ——			0.48 ——			
Aggregate	—— crushed, max. dia 20mm ——						
Mean static compression strength; 150x300 mm cylinder σ_c (N/mm^2)	22.7 ——			43 ——			
Mean flexural strength; center point loading test σ_f (N/mm2)	4.64 ——			8.08 ——			
Mean static tensile strength; cylinder splitting test. σ_T (N/mm^2)	1.85 ——			3.58 ——			
Poisson ratio (%)	24.2 ——			21.8 ——			
Mean dynamic modulus of elasticity; ultrasonic method test E (N/mm2)	3.6×10^4 ——			4.3×10^4 ——			
Mass of steel (kg)	0	0	0	47	38	25	21
Steel VS. Conc. ratio by weight (%)	0	0	0	3.26	2.64	1.74	1.46
Steel area ratio (%)	0	0	0	1.890	0.945	1.890	1.890

THE BIRD'S EYE VIEW
OF DOLOS MANUFACTURE

DOLOS MOLDING

CURING

PLACING

DEMOLDING

DOLOS SPECIMENS

Fig.6 DOLOS SPECIMES PREPARATION

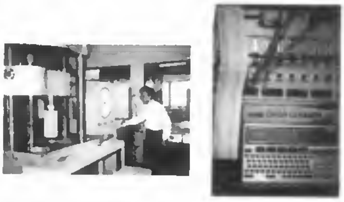


Fig.7 100 TONS UNIVERSIVAL
MATERIAL TESTING MACHINE

Fig.8 TEST HAMMER

Fig.9 ULTRA-SONIC
PULSE MEASURING
UNIT

Experimental Method and Equipment

Three different types of test were used (Fig. 4). The drop test simulates the wave induced rocking of the units. The pendulum tests (1) and (2) simulate the frontal and transverse impact from pieces of broken units that are thrown around by the waves.

The experiment was carried out on a test platform. In the drop test, one end of the dolos is lifted to a predetermined height and then dropped by means of a quick release hook (Fig. 10 & 11). In the pendulum tests (1) and (2), the pendulum is pulled back a certain distance and then released.

The pendulum is a steel cylinder mould with wall thickness of 10 mm, filled with the same type of concrete as used in the dolos. Its weight is 1/5 of the dolos weight. The pendulum is suspended on two wires hanging on a steel gantry.

Before dynamic testing the dolos specimen were tested by using test hammer and ultronic-sonic pulse measuring unit (Fig.12) to be sure of good quality.

In the drop tests, we measured the fall height (the vertical distance from the base to the center of the fluke end); the initial drop of 100mm was gradually increased in increments of 20mm. In the pendulum tests, we measured the draw back distance (the shortest distance between the surface of the pendulum and the impact point on the dolos); and it was gradually increased from 300mm in the first strike, in increments of 20mm.

Because of the rebound, the dolos was jerked back against the steel packing block after each pendulum blow.

The concrete surface was carefully examined after each strike and the width and extent of the cracks were recorded.

With the purpose of examining the fracture, the loading on the plain concrete was continued until the unit broke into two pieces. Failure of the reinforced units was taken as occurring when the crack width exceeded o.15mm which examined by a crack detection microscope (Fig.13).

Fig.10 DROP TEST QUICK RELEASE HOOK

Fig.11 PENDULUM TEST QUICK RELEASE HOOK

Fig.12 ULTRA-SONIC PULSE VELOCITY MEASUREMENT OF DOLOS

Fig.13 CRACK DETECTION MICROSCROPE

TEST RESULTS

Maximum Fall Height

The average maximum fall height of the pendulum (or the dolos center of gravity) was defined as the point at which the plain concrete dolos broke into two pieces and the crack width of reinforced units exceeded 0.15mm.

The test results of average maximum fall height of dolos destruction for the seven types used are shown on Fig.14. It is quite obvious that the Pa-Tou-Tzu fishery port model is the best one. For chamfered corner dolos made of plain concrete, a strength of 34.5 N/mm² (5000 psi) is better than that of 20.7 N/mm² (3000 psi), and for the same strength of 34.5 N/mm² (5000 psi), the chamfered corner type is better than the enlarged fillet corner type.

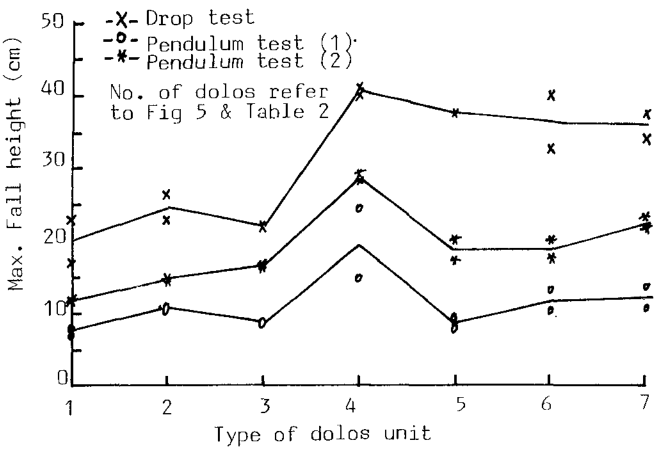


Fig 14 Max. Fall Height of Dolos Destruction

Fracture Types

The fracture types of dolos destruction are shown on Fig.15 and Fig.16 and described as follows:

Drop test: There were two fracture types. In the first type, cracks started at the top of the stem-fluke corner and spread to the bottom of the stem. In the second type, the fractures not only developed in the stem-fluke corner but also in the middle part of the bottom of stem, and spread to the top of the stem.

Pendulum test (1) : In one type, cracks started at the bottom of the stem-fluke corner and spread to the top of the stem. In another, cracks started at the top of stem-fluke corner and spread to the fluke.

KAOHSIUNG HARBOR MODEL
DROP TEST

PA-TOU-TZU PORT MODEL
PENDULUM TEST(1)

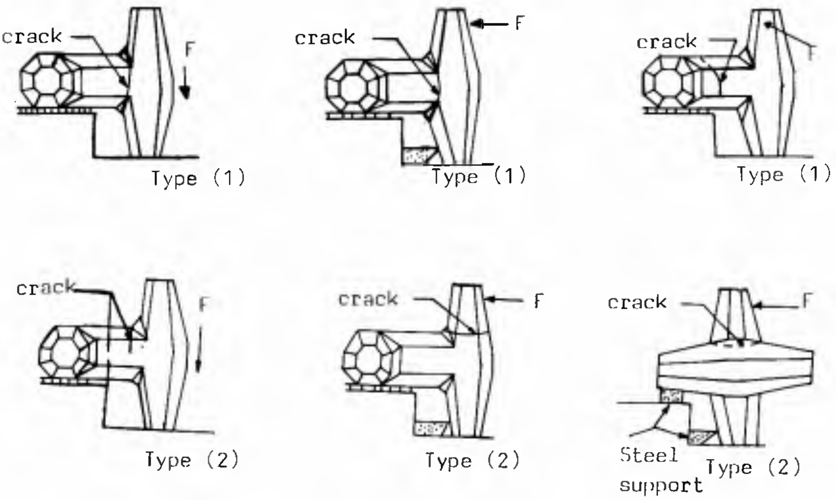
PLAIN CONC FILLETED
PENDULUM TEST(2)

PLAIN CONC CHAMFERED
DROP TEST

KAOHSIUNG HARBOR MODEL
PENDULUM TEST(1)

SU-AO HARBOR MODEL
PENDULUM TEST(2)

Fig.15 TYPICAL FAILURE TYPES UNDER DYNAMIC TESTS



(a) Drop test (b) Pendulum test (1) (c) Pendulum test(2)

Fig 16. Typical cracks and fractures under dynamic tests

Pendulum test (2) : The cracks either started in the middle part of the top of the stem and spread to the bottom of the stem, or started at the top of the stem-fluke corner and spread to the fluke. For reinforced units, the crack spread is fast in the fluke and very slow in the stem.

Maximum Stress vs Fall Height

Test data for the three kinds of plain concrete units were input into eq.(1), eq.(2) and eq(3). The constant factors were determined by test results and are shown in Table 3. The maximum tensile stress on the dolos is proportional to the square root of the average maximum fall height of the pendulum. This relationship is shown in Fig.17. Therefore by comparing with the plain concrete cylinder splitting test data, the mean static tensile strength of each type of dolos model can be obtained and is shown in Table 4.

TABEL 3. FACTORS IN EQ.(1)-(3) DETERMINED BY TEST RESULTS

Test type	Factor	34.5N/mm² Chamfered	34.5N/mm² Filleted	20.7N/mm² Chamfered
Drop	C1	0.116	0.123	0.074
Pendulum(1)	C2	0.333	0.372	0.227
Pendulum(2)	C3	0.286	0.266	0.178

TABLE 4. COMPARISON OF MEAN STATIC TENSILE STRENGTH IN REINFORCED UNITS (N/mm²)

Test type	Pa-Tou-Tzu fishery port	Ksohsiung Harbor	Su-Ao Harbor	Burcharth's paper
Drop	4.628	4.454	4.379	4.349
Pendulum(1)	4.912	3.273	3.829	3.894
Pendulum(2)	4.595	4.132	4.155	4,540

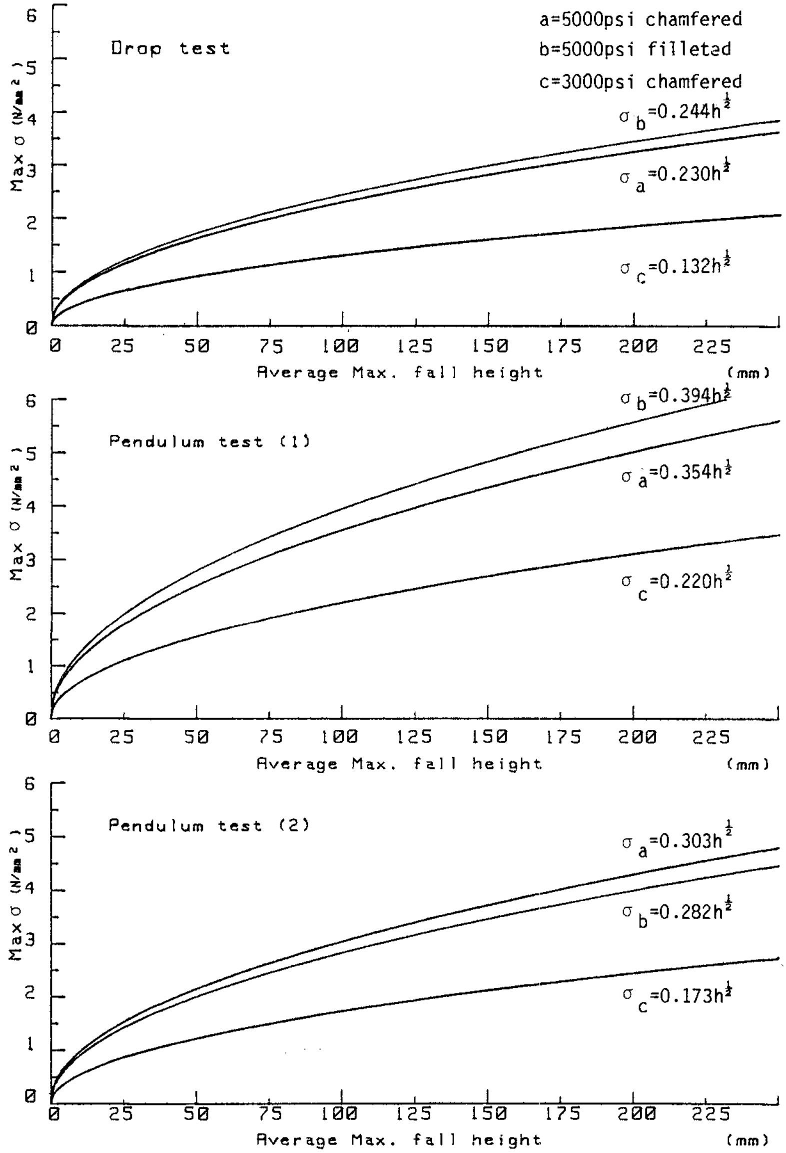


Fig 17 Max. tensile stress vs average max. fall height

DISCUSSION

1. Fig.14 shows that the dynamic strength of reinforced concrete units is better than that of plain concrete, therefore putting suitable rebar into the tension zone will reinforce the tensile strength of dolos.

2. Wave forces are random, therefore the rebar should be distributed throughout the stem and fluke of the dolos. In the Su-Ao Harbor model, the rebar in the fluke deflected to one side, and the dynamic strength was low. In the Kaoshiung harbor model, the quantities of rebar in the stem were inadequate. There is no rebar in the fluke of the Burcharth model, so it is easy to break the fluke. The rebar design in the Pa-Tou-Tzu fishery port model is better, and therefore it shows the best performance in the dynamic tests.

CONCLUSIONS

1. The cracking behavior in dynamic tests coincided with those of site observation. In the design of dolos, the design criteria should consider both the hydraulic and mechanical instability.

2. Comparing the results for units of both reinforced and plain concrete, it is clear that reinforcement of the unit could reduce the magnitude of the stress concentration, but a suitable rebar arrangement must be made to ensure durable behavior, otherwise corrosion of rebar may occur.

3. From the dynamic tests, it was found that cracks start at the corner between the stem and fluke. If the cross section of this corner is increased, then the free length of fluke will be shortened and the probability of dolos fracture will be decreased.

4. Fracture by frontal impact is more severe than that of transverse impact which in turn is more severe than that of the drop test.

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