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WATER STORAGE TANKS IN PAPUA NEW GUINEA AND THE EFFECTS OF SEISMICITY

by

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1. INTRODUCTION

"Seismic activity in Papua New Guinea is very high, comprising five to ten per cent of the world's total earthquake occurrences. Earthquakes potentially large enough to cause considerable damage occur within PNG at an average rate of about ten per annum" (1).

The PNG Advisory Committee on Seismology and Earthquake Engineering suggested that the Division of Building Research, CSIRO, might collate such data as was available on cost-in-use of corrugated galvanised iron (CGI) tanks, seismicity predictions, and alternative treatments, materials, and designs for tanks, to enable an assessment to be made of the magnitude and significance of the problem of damage to domestic water storage tanks by earthquakes.

Among the cities and towns of Papua New Guinea only Port Moresby and Arawa enjoy a full, reticulated water supply. There is therefore a considerable dependence throughout the country upon rain-water storage tanks, although both Lae and Rabaul have partial reticulation systems for bore water. Regrettably, the ubiquitous CGI tank is highly susceptible to earthquake damage (Fig. 1); so much so that it has become a criterion for assessing the intensity of an earthquake. (See Appendix 1).

Considering those towns with a water supply from tanks, it is probable that Rabaul, Madang, Wewak and Lae are those most likely to experience a severe earthquake. Tanks at risk in these towns are estimated (See Appendix 2) to total 12,000 and the replacement cost to be at least $1.6 million.

A wider estimate including all of Seismic Zone A of the PNG Building Regulations, 1971 (Fig. 2) would place the value of the tanks at risk in the region of $2.5 million.

Several factors dominate any attempt to come to grips with the subject of this report: the major role played by corrosion in determining CGI tank life (i.e. earthquake damage is a relatively minor cause of tank failure), the wide variation in tank life and cost at various locations in PNG and the general sparsity of actual data.

In PNG, the ownership of most houses and many other buildings lies with one or another of the Governmental or quasi-Governmental agencies with the result that the Department of Public Works (PWD), the former Commonwealth Department of Works (CDW), the Australian Department of Civil Aviation (DCA) and the Electricity Commission of PNG (Elcom) are between them responsible for much of the building maintenance within the country. The authors thank the many officers of these bodies for the information freely given concerning the cost and performance of various tanks and the benefits of alternative treatments and materials. Two other possible sources of data, viz. the Australian Defence Department and the Housing Commission of PNG, were found to have installed reticulation systems or to operate largely within areas having reticulated systems. Finally, it was not considered feasible to obtain data from private or commercial owners of buildings.

Numerous accounts are available of damage and destruction resulting from earthquakes in the various countries of the world subject to high seismicity but, as might be anticipated, the emphasis is on structural damage. Damage to services, including water, is usually treated in meagre fashion and frequently dismissed with "water supplies were disrupted" or "many elevated water tanks were thrown down". A notable exception to this tendency is the report by Steinbrugge and Moran (2) on the 1952 Kern Country (California) earthquake. In Appendices R and S, the behaviour of elevated and ground tanks is followed in considerable detail but unfortunately for present purposes, the tanks studied were significantly larger than domestic tanks.

2. TANKS - MATERIAL, COST, AND DURABILITY

(a) Corrugated Galvanised Iron

The standard material for tanks is a 0.56 mm (24 gauge) steel corrugated with a pitch of 76 mm (3 inch) and carrying a zinc coating of 550 g/m^2 (2.0 oz/sq.ft). Tanks are formed from curved sheets by rivetting and soldering the joints (Figure 3).

The cost of a 9000 ℓ (2000 gallon) tank was variously quoted (1973) as \$80-\$120 ex factory or between \$120 and \$160 when installed, depending on location. The concrete base for a 9000 ℓ (2000 gallon) tank was estimated to cost \$140.

Estimates of tank life from several sources are drawn together in Table 1. Certain of the figures (as is the case for the PWD values for Daru and Kerema) have considerable reliability while others are tentative, but overall they give the impression that a life of 3 years in a coastal situation and 7 years in the highlands would be typical.

TABLE 1

ESTIMATED LIFE OF CGI TANKS

LOCALITY	TANK LIFE IN YEARS ESTIMATED BY		
	PWD	CDW	DCA
Daru	4	2	-
Kerema	2	-	-
Lae	-	6	-
Madang	7	-	3
Mt.Hagen	5	-	-
Magarida	<2	-	-
Rabaul	-	5	-
Highlands	-	6 to 7	6 to 8

Coronus dust is considered by DCA to adversely affect the life of tanks at Madang but details were not available. Coronus is the pidgin name for unconsolidated corralline limestone used as a road surfacing material.

(b) Protected CGI

(i) Metaphosphate salts: Excellent life is obtained from CGI tanks in rural districts having moderate to low rainfall but in marine environments or areas of heavy rainfall life may be seriously reduced. Considerable improvement has been reported by Stein (3) under these conditions by the inclusion of glassy metaphosphate salts in the water of a new tank, but attempts to use a proprietary product* in PNG appear to have encountered practical problems.

The chemicals in the suspended tube (which is hung inside from the top of the tank on installation) are hygroscopic, and instead of being dissolved by water when the tank is first filled, as the manufacturer intended, they tend to dissolve in moisture drawn from the humid air prevailing in PNG, and drip in a concentrated solution on to the bottom of the tank, and this causes corrosion. Furthermore, wetting of the crystals before the tank is filled is said to alter their solubility. The corrosive drip could be overcome with moderate trouble and expense by positioning a cheap plastic bucket beneath the suspended tube or by arranging to partially fill the tank with water on installation. If these problems can be successfully avoided, worthwhile increases in the life of CGI tanks (the Australian trials indicated an increase of 2/3) can be expected for a minimum outlay; a plastic "sausage" of prepared salts costs $2 and one of these is used for each 4500 ℓ (1000 gallons) capacity of the tank. The cost, including insertion, for a 9000 ℓ (2000 gallon) tank would be $5-$6.

(ii) Tar-epoxy paint: Two-pack, coal-tar epoxy paint applied with a minimum of two coats and 0.15 mm (0.006 in.)

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* 'Tect-a-Tank', John Lysaght (Aust) Pty. Ltd.

film build is a recommended method of protection for galvanised steel.

Reports from PWD indicate that tar epoxy applied inside and out increased the life of tanks at Magarida from 18 months or 2 years to perhaps 5 years and at Daru from 4 years to as long as 12 years.

Nine litres (2 gallons) of coal-tar epoxy mixture, costing $8.40 per gallon, are required to apply one coat to the inside and outside of a 9000 ℓ (2000 gallon) tank. Labour time will be about 4 hours per coat, at an hourly rate of $1, making the total cost of protecting the tank with two coats between $40 and $45.

(iii) Cement-based coatings: A number of cement-based treatments have been used from time to time to extend the life of CGI tanks, but exact costs and performance are not known.

A trial at Rabaul in 1965 using cement-linseed oil-goldsize (goldsize is a mixture of copal varnish and yellow ochre in boiled oil and turpentine) is reported to have extended the life of the tank from an anticipated 3 years to 5 years. The PWD Building Research Station have a trial proceeding at Porebada which began in 1971. A cement-PVA-bentonite brush-on coating developed corrosion patches after a year, and has been discontinued. A cement render over chicken-wire is still performing satisfactorily after 2 years. The base tank in this case had been previously discarded because of excessive rusting.

Costs for these methods would be in the region of $10 for the brush methods and perhaps $20 for the render method.

(c) Bolted Flat Plate

A small number of heavy-gauge bolted or welded tanks, often relics of World War II, are giving excellent service in PNG. Tanks of this type, such as the Braithwaite*, may be considered as possessing full resistance to earthquake shock but are too costly for domestic application.

Forming a separate category is the lighter, flat-plate type of bolted tank made from 1.6 mm (16 gauge) galvanized steel (Fig.4). These tanks are assembled on site from preformed plates of convenient size and water leakage is prevented by a bead of mastic compressed within the joints. The tank has two significant advantages for Papua New Guinean conditions: it will transport in a knocked-down form, and no special skill is needed for erection.

The steel used has a zinc coating weight of 550 g/m^2 (2·oz/sq.ft) and the little that is on record regarding life against corrosion seems to indicate that the life is significantly better than that of a CGI tank. For this report a somewhat conservative figure of 10 years has been adopted.

A 1971 quotation# gave the price in store, Port Moresby, as $205 for the 4500 ℓ (1000 gallon) size. It is estimated that assembly would not take more than 10 man-hours and that completed cost would be $215.

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* Braithwaite ¢ Co., Great Bookham, Surrey, U.K.
# Statham Ltd., Charlestown, N.S.W.

(d)

(d) Rigid Plastic

(i) Glass fibre reinforced polyester: Two types of glass fibre reinforced polyester (FRP) tank have now been in limited use in Papua New Guinea for several years. One is imported from Queensland in kit form*. The other is made in Port Moresby# and takes the form of an opposing pair of truncated cones which are bolted together on site.

Certain difficulties have been encountered in the field with both types. The tank in kit form, although admirably suited to transport in PNG, requires a certain degree of skill and familiarity with resins in assembly (Fig. 5). The chief difficulty, however, has been with insufficient shelf-life of the resins supplies with the kit. The double-cone tank (Fig. 7), although readily assembled, has proved to be subject to damage in transport and in separating the cones nested for economies in handling. Furthermore both tanks while under test at the Building Research Station of PWD were found to be sufficiently translucent as to develop excessive algae growth within the tank to the point that the water was judged non-potable.

However all these points spring largely from the novelty of the tanks and will be overcome quite readily should they be used in greater numbers. The Department of Social Development and Home Affairs has issued a directive that FRP tanks are to be supplied in areas subject to salt spray or earthquake. Since these installations are mixed, i.e. both CGI

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* Supplied by Fontana Distribution Co., Banyo, Queensland

\# Monier Fibreglass (PNG) Pty. Ltd., Port Moresby and FRP tanks are used at each site, a useful direct comparison should be forthcoming in due course.

In 1971, the FRP tank in kit form cost $234 into store at Port Moresby for the 4500 ℓ (1000 gallon) size. Assembly of the tank took 20 man-hours giving a final cost of $254. The cost in store, Port Moresby, in 1971 of the double-cone tank was $174 and with 3 man-hours needed for assembly, the complete cost taken as $177.

Glass fibre reinforced polyester used in these tanks has a limited history with respect to durability when used for water tanks. It is known that a number of FRP tanks were installed on Willis Island, Queensland (latitude 16°S) in 1963; after 8 years service the only deterioration reported was some abrasion of the surface. It is understood that the first FRP tank installed in PNG went into service at Daru in 1967 and is presumed to be still operational. The performance of FRP roofing sheets has some relevance. These are believed to have a life expectancy of 10 years in the humid tropics but can vary enormously depending on the formulation. By comparison, rain-water tanks would receive less solar radiation and may therefore last considerably longer, possibly 20 years.

(ii) Polyethylene: Rigid one piece tanks of low-density polyethylene are manufactured in Australia by rotational moulding*. Polyethylene is approved by the Food and Drug Authority of USA for the storage of potable water, it is taint-free and, because the tanks are made with a black outer

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* ACI Plastics Pty. Ltd., Moorabbin, Vic.

layer opaque to solar radiation, problems with the growth of algae are unlikely.

The largest tank in production has a capacity of 3000 ℓ (600 gallons) and costs $360 ex factory. Polyethylene is subject to degradation when exposed to solar radiation. This can be minimized by incorporating carbon black into the formulation, and then a life of 7 to 10 years could be expected for a fully exposed tank.

(e) Plastic Membrane

The Department of Public Works included a butyl rubber membrane tank (Fig. 6) in the 1971 tank comparison tests. Initially, water from the tank was considered to have a taste but this disappeared with use. The rubber walls of the tank apparently attract attention, and PWD had to repair a considerable number of punctures caused by pointed objects - including arrows.

The 1971 cost of the 4500 ℓ (1000 gallon) tank, imported from New Zealand#, was $199 into store at Port Moresby. Assembly of the tank took 8 hours so that the final cost can be estimated as $207.

Bag tanks of nylon-reinforced polyvinyl chloride have been suggested since the material is relatively inexpensive. The Department of Health has experimented with "Wavelock" (PVC films reinforced by nylon filament) as a lining for rain catchment areas (for village water supplies), but has

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Blades Plastics Ltd., Auckland but now Dunlop N.Z. Ltd., Christchurch.

discontinued its use, partly because of degradation by the sun.

(f) Concrete

Concrete cisterns are a recognised form of domestic water storage in many parts of the world but are disadvantaged by a high initial cost. A few installations of this type have been reported from PNG, e.g. several houses in Rabaul are said to have rectangular concrete tanks, the covers of which double as the floors to the verandahs.

Another form of concrete tank also in use in Rabaul is made from an up-ended spun-concrete pipe. In 1974, the cost at the factory* of a pipe and lid giving a capacity of 9000 ℓ (2000 gallons) was $210. Delivery charges within the vicinity of Rabaul are estimated at $50 and the cost of the concrete slab base at $60. Some seepage has been experienced at the junction of the pipe and slab but in other respects the tanks are considered satisfactory. Tanks made in this way are known to have been in service since 1967.

(g) Ferrocement

Ferrocement is well established as a suitable material for domestic and farm-water storage tanks in New Zealand where over 50 manufacturers are in production. A well-made ferrocement tank can be expected to last for many years: an Australian manufacturer of ferrocement water tanks# offers a 25 year guarantee. It is of interest that a ferrocement rowing boat built in 1887 was still afloat and in good con-

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* Vulcan Concrete Pty. Ltd., Rabaul

\# Everlast Concrete Tanks Pty. Ltd., Albury, N.S.W.

dition in 1967 at the Amsterdam zoo. Several ferrocement tanks are in use in Rabaul: one, located near the town market, is reported to have been built in 1958 and another, on Matupit Island was built in 1967.

A 1974 estimate for the costs of a 13500 ℓ (3000 gallons) tank designed by PWD in Rabaul comprises $250 for materials and $170 for labour.

(h) Timber

Timber is a traditional material for storing liquids, e.g. beer, and has been widely used for rain-water storage in Europe and America. The general availability in PNG of timber and of wood-working skills make the material of interest, particularly since the properties of timber structures are well suited to the vibrations and shocks of earthquakes.

Timber tanks can be of two types: a tight construction such as a boat or a barrel or an easier, loose construction that relies on a plastic sheet liner or a coating of mastic for watertightness.

A timber tank incorporating a replaceable plastic liner is thought to have some merit particularly for PNG conditions since it would be relatively easy to repair should it suffer damage in an earthquake. Even in the extreme case where a tank was dislodged from a stand it would presumably be possible to nail the tank together once again and drop in a new plastic liner.

In the absence of naturally durable species, the use of timber preserved by pressure-impregnation with "fixed" salts might be considered since, even if the tank water should by accident come in contact with the timber, the rate of extraction of potentially harmful substances is reputed to be too slow to constitute a threat to health. It is recommended, however, that any unabsorbed salts be washed from the surface of the timber.

For strength and cleanliness, the tanks would include a lid and consequently the plastic liners would be fully protected from sunlight and physical damage and in this respect differ significantly from the membrane tanks discussed in section (e). While it is feasible to include an outlet tube in the liner, a syphon would be a better and easier way of drawing off the water.

Several materials can be suggested for the liner. Polyethylene should be durable and is probably the cheapest. It has the advantage that an extrusion plant is now operating in Lae and that several polyethylene converters are already in business in PNG with experience in heat-welding of the film. A thickness of 0.20 mm (8 thousandths of an inch) is considered reasonable and cost of a liner for 9000 ℓ (2000 gallon) capacity is estimated at $10. Plasticised PVC is an alternative material and once again there are processors in PNG with experience in making-up this material. It is necessary to specify non-toxic grades of PVC as there is some extraction of the additives during use. The recommended thickness is 0.75 mm (0.03 in.) and the cost of a liner is likely to be in the region of $50. An excellent but more expensive material is Hypalon* which should offer a life well in excess of 20 years. (Some external applications in Florida, U.S.A., have been in service for 17 years). Hypalon is approved for use with potable water by the Food and Drug Authority of U.S.A. The recommended sheet is 0.75 mm thick (0.03 in.) and is reinforced with nylon scrim. Fabrication is by means of high-frequency welding. The estimated cost of a liner is $90.

The cost of the timber shell is estimated at $150 based on the use of timber preserved by "fixed" salts. The durability of such a tank is a matter of some conjecture but it is not thought unreasonable to assign a life of 12 years to the composite structure.

(i) General Comparison

Data and estimates for the various alternative materials have been drawn together in Table 2 and arranged in order of increasing annual costs. Since it is the cost in place which is relevant, an attempt has been made to estimate the cost of transport and connection at a site adjacent to a coastal town, making due allowance for the weight and bulk of the tank. Where costs were obtained prior to 1974 an increase of 5% p.a. has been allowed in arriving at the figure shown in the table.

The life listed under the heading "Corrosion only" is the number of years estimated to failure through corrosion, embrittlement or rust in the absence of earthquake.

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* Trademark, Du Pont.

TABLE 2

A COMPARISON OF ESTIMATED TANK PERFORMANCE*

Tank Material	Capacity (litres)	Cost ($)		Corrosion only		Corrosion plus seismicity		Resistance to Earthquake Damage
		Tank	T and C **	Life (years)	Cost per 1000ℓ per year ($)	Life (years)	Cost per 1000ℓ per year ($)	
Ferrocement	13500	420	20	25	2.3	16.7	2.9	good
Timber - polyethylene liner	9000	160	30	12	2.3	9.7	2.8	very good
Concrete pipe	9000	270	50	25	2.4	16.7	3.1	fair
CGI + tar-epoxy	9000	155	25	10	2.6	8.3	3.0	very poor
CGI+ phosphates	9000	115	25	7	2.7	6.1	3.0	very poor
FRP (conical type)	5500	200	20	20	3.1	14.3	4.0	fair
CGI + cement	9000	-------- Insufficient data ---------			-	-	-	very poor
CGI	9000	110	25	5	3.4	4.5	3.8	very poor
FRP (kit type)	4900	290	15	20	5.4	14.3	6.8	fair
Butyl rubber	4500	240	15	10	7.4	8.3	8.6	very good
Bolted flat plate	4500	250	20	10	7.8	8.3	9.1	fair
Moulded polyethylene	2750	≈ 460	15	8	27.2	6.9	30.8	good

* A simple economic criterion for deciding the acceptability of costly treatments (or the use of materials more expensive than CGI) to increase the life of tanks against deterioration is that the percentage increase in life must be greater than the percentage increase in the installed cost of the tank. It is essential to use installed cost rather than the simple cost of the tank 'ex works' because labour and freight costs can greatly alter the economics of a given proposal

** Transport and Connection charges.

The figure shown as cost per 1000 litres per year is made up of the annual depreciation plus interest at 6% on the average depreciated value of the tank together with the yearly share of the transport and connection charges.

The cost comparisons are not entirely realistic in that economies through scale are possible in some cases: the galvanized steel flat plate, FRP kit, and butyl rubber tanks are available in 9000 ℓ (2000 gallon) capacities and larger. Furthermore, these tanks were costed on the basis of a single import whereas comparison is being made with the CGI tank manufactured in large numbers within PNG. However, while the import of substantial numbers of the larger tank may give a significant reduction in the cost per 1000 ℓ per year, it is not thought likely that the rank order would change.

The first 5 tanks of the table may be considered as having a somewhat similar economic performance giving a cost-in-use of $2-$3 per 1000 ℓ per year so that selection may be made on the basis of first cost and earthquake resistance. The timber/polyethylene tank appears to be outstanding in this regard but is unproven. The conical FRP tank and the untreated CGI tank give figures between $3 and $4 but the remainder of the tanks return costs-in-use which are 50% higher and more.

3. BEHAVIOUR OF TANKS DURING EARTHQUAKES

(a)- A Review of Theoretical and Experimental Studies

The shock waves of an earthquake, together with reflections and diffractions, form complex vibrational spectra which result in the near random, three dimensional ground movements typical of a seismic disturbance. Although it is possible to recognise the several basic ground waves in a seismograph trace and consequently to assign values for period and amplitude, this can usually only be achieved for recordings made at appreciable distances from the hypocentre. Attempts have been made to equate acceleration values with the steps of the scales of felt intensity, but with limited success because building damage and other evidence upon which intensities are assessed are also influenced by the duration and wave shape of the motion. In a similar way, the accelerations specified in the various building codes cannot be used to deduce the actual accelerations to be withstood since they merely imply that a building of a particular type, if constructed with a strength indicated by a certain acceleration will probably withstand most earthquakes. The installation of strong-motion recorders or accelerographs in selected buildings and sites is now routine in a number of countries and this practice will eventually provide adequate information regarding the characteristics of damaging ground movements.

Studies of the behaviour of structures and building components under seismic excitation and which involve simulated earthquakes have, of necessity, adopted simplified movements e.g. uni-directional harmonic oscillations with periods in the range of 0.05 to 2 seconds and accelerations between 0.01 and 1 g.

Hoskins and Jacobsen (4) adopted this approach when they investigated the pressure changes in a rectangular tank mounted on a shaking table excited by a pendulum bumper. The response of a liquid-filled tank subject to an impulsive horizontal ground displacement was analysed by Jacobsen (5) who prepared graphical relationships which permit ready calculation of effective hydrodynamic mass and mass moment of the liquid. The work was extended by Jacobsen and Ayre (6) to include extensive experimental verification, the distinction between full and part-full tanks having rigid covers, and wave profiles of the liquid.

It is probable that even when full, the behaviour of domestic water tanks will be that of a part-full tank. This is because the cover to the tank is usually non-rigid and because the presence of an overflow pipe will lower the water level to below the critical height.

Jacobsen and Ayre (6) showed that the removal of only 2% of water from a full, rigidly-covered tank is sufficient to reduce the ratio of effective mass to actual mass from unity to approximately 2/3 which is the value for an open tank.

Using the relationships of Jacobsen (5) it is of interest to compare the overturning moments generated in the upright and squat versions of the 4500 ℓ (1000 gallon) FRP tank of kit type when subject to an impulsive translatory force equal to 0.2 g. The upright tank has a diameter of 1839 mm (6 ft) and equal height; the squat tank has a diameter of 2510 mm (8 ft 3 ins) and a height of 910 mm (3 ft). Wall thickness is assumed to be 9 mm (3/8 inch) and the material to have a density of 1.8 g/cm^2 (112 lbs/c.ft).

	Upright	Squat
(a) Moment due to mass of tank wall	320 N.m	110 N.m
(b) Moment due to effective mass of water	5170	1260
(c) Hydrodynamic couple acting on tank base due to mass of water	5480	2580
Total overturning moment	10970 N.m (8110 ft-lbs)	3950 N.m (2920 ft-lbs)

i.e. total overturning moment operating on the upright tank is almost 3 times that applicable to the squat tank.

There is, in the literature, appreciable reference to the vibrational analysis of cylindrical shells and, although much of the work described refers to rocketry or blast effect, it is still pertinent to a consideration of seismic excitation. In point of fact, Ayra, Thakkar and Goyal (7) determined the vibrational response of tanks containing liquids to ground motion with a view to the civil engineering ramifications. In addition, Arnold and Warburton in 1949 (8) and again in 1953 (9) described the experimental determination of the nodal patterns in a freely supported cylindrical shell which was vibrating at its resonant frequencies, and dynamic analysis was employed by Di Maggio (10) and Baron and Bleich (11) in a study of open, cylindrical shells. Baron and Skalak (12) extended the analysis to include shells partially filled with liquid.

(b) CGI Tanks

(i) Mode of failure: Depending on the intensity of the earthquake, damage may range from a mere hastening of pinhole leakage caused by the jarring loose of protective corrosion products to the incontrovertible loss of the tank through being dashed to the ground with intermediate forms of damage comprising bursting of the soldered seams and the intriguing "concertina" collapse (Fig. 9).

The relative number of tanks in each category of damage is not known and little is on record regarding the damage sequence which may be expected during an earthquake although Denham (13) includes an account of the behaviour of water tanks at Brandi High School which, during the Wewak earthquakes of 1968, were observed to rock a foot off their stands before being concertinaed.

There is general agreement amongst observers that tanks are more prone to damage when they are partly full, say between 1/3 and 2/3 full, presumably as a result of surging of the water within the tank during the earthquake.

(ii) <u>Proportion of tanks damaged</u>: Although the isoseismal maps published for most major earthquakes enable broad estimates to be formed of tank loss, relatively little information was forthcoming regarding the actual proportion of tanks damaged by a particular earthquake. The Madang earthquake of 1970 represents the main source of data which is shown below

Information Source	Percentage of tanks replaced At -	
	MADANG	MT. HAGEN
DCA	50 - 65	40
PWD	50	-
Elcom	30	-

The felt intensity of the shock on the M.M. scale was reported by Everingham (14) to be VII at Madang and VI at Mt.Hagen.

PWD reported that after an earthquake at Medina, 20% of the tanks needed replacing. The earthquake was probably one that occurred in the North Solomon Sea on 4 October 1967 and was considered to produce felt intensities of MM V in the Medina area (i.e. 80 km - 50 miles - S.E. of Kavieng).

(iii) Influence of tank support and restraint: High stands for water tanks are normally restricted to institutional use but do not perform well in earthquakes (Fig. 8) partly because of the coupling that exists between the fluid system and the tank/stand system (Carder (15)).

Houses are supplied either with a gravity feed system involving moderate elevation on a tank stand (Fig. 10) or an electric pump system which enables the tank to be placed at ground level on a concrete pad (Fig. 11).

Little evidence is forthcoming as to the relative advantages of the two systems when considering damage to tanks but opinions generally are that while the sway generated by a tank stand may be more likely to cause the tank to overturn, the rigidity of a tank base may mean that the tank is more apt to burst or 'concertina'. However, a tank dislodged from a ground-level support may still be of some service but a tank which has fallen from 3 metres will be beyond consideration.

Various attempts have been made to restrain the tanks and prevent overturning. One method employed a number of wooden cleats, shaped to fit the bottom corrugation of the tank, which were bolted to the tank base or support (Fig. 12). During an earthquake, the metal of the tank tore at the cleats. Another technique used a wooden cross on the top of the tank pulled down to the base by four long bolts. In these cases, the tanks failed at the seams during an earthquake. The general impression emerges that the CGI shell has insufficient strength to control the water surges during an earthquake and that less damage may result if the tank is allowed to follow the movement of the water.

Recognising that tanks will tend to move independently of each other and of associated structures, it is customary practice to include a short length of flexible hose in the coupling to the service piping and between adjacent tanks. However instances have been noted when tank damage has been minimal but water has still been lost because of ruptured connections. It is believed that the length of hose employed could with advantage be lengthened from 75 mm to more than 300 mm (a foot or more).

(c) Other Tanks

Compared to CGI tanks, insignificant numbers of tanks made from other materials are in service and little is known about their behaviour in an earthquake.

FRP tanks in Rabaul and Madang are reported to have survived recent earthquakes but the circumstances are unknown to the authors. The concrete-pipe and ferrocement tanks in Rabaul were not damaged by the 1971 earthquakes but the felt intensities in Rabaul itself did not exceed MMVI so they are as yet unproven. Bolted steel plate tanks were inspected at Gaulim and Keravat where felt intensities reached MMVIII in the same earthquakes: the cover of one tank was distorted and some seepage was occurring from the other but otherwise the tanks were in good condition. At Makurapau, near Rabaul, which experienced MMVII or VIII during the Kokopo earthquakes of August 1967, a 10000 gallon bolted tank is reported to have burst (16).

In general, damage from overturning is likely to be as serious as for CGI tanks (with the possible exception of the rubber bag tank) but otherwise better performance may be expected as the "concertina" effect will be absent and the bursting strength of the heavier tanks will be greater. Some reservations may be held in this regard for the FRP tanks as their flat ends may be susceptible to bursting damage.

4. THE CONSEQUENCES OF A DISRUPTED WATER SUPPLY

In a major earthquake it is quite feasible for virtually all of the tanks at risk to be damaged to the point of needing replacement. Water is vital to the individual and the community for drinking, cooking, washing, sanitation, and fire fighting. It takes time to restore storage facilities, and in the meantime emergency arrangements must be made.

Although, elsewhere, fire is held to be a potentially destructive partner of earthquake, officers of civil defence and fire fighting organisations believe the risk to be relatively low in PNG. This is firstly because of the absence of open fires and heating appliances from within most buildings and secondly because of the generally small size but wide separation of the buildings themselves.

One view of what is needed by way of emergency water supplies is given in the following extract from "Proposed Minimum Standards for Permanent Low-Cost Housing" prepared by the Agency for International Development, Division of International Affairs, Department of Housing and Urban Development, U.S.A.:-

> "B-603 Emergency Supply
> Where .... it is thought advisable by the local health authority .... that a reserve water supply is desirable in order to ensure a potable supply and/or to ensure the proper functioning of sanitary facilities, a supplementary tank or cistern shall be provided. In case of need, these facilities can also be used for fire purposes.
>
> The capacity of supplementary tanks shall be a minimum of 80 (US) gallons per person, or a minimum of 240 (US) gallons whichever is greater".

Alternatively, where conditions are favourable, emergency water may be obtained from natural sources although sterilization may be required. Some aspects of sterilization of surface water are studied in Appendix 3 and the costs involved are compared with the cost of storage of emergency water.

5. THE INTERACTION OF SEISMIC DAMAGE AND DURABILITY

In the absence of earthquake damage, tanks will eventually fail through corrosion or weathering. If the life against corrosion or weathering is short, and the return period* of a major earthquake is long, the cost that can be economically justified for an effective reniforcement system for the tanks will be relatively small.

Let the return period of an earthquake severe enough to damage all tanks be N years, the life of a tank under non-seismic conditions be n years ($n < N$), and the cost of replacing a tank be C. The number of tanks used in N years, because of corrosion only, will be N/n, but under seismic conditions it will average $(N/n) + \frac{1}{2}$. This is to say that the average effect of a major earthquake (MMVIII or higher) will be half way between two extremes: shock the day after a brand new tank was installed, and shock the day before a tank would have failed by corrosion. In the first extreme an additional tank will be required but the other extreme has no significant effect on the number of tanks needed.

Thus the effect of seismicity is to increase the cost of maintaining a water tank throughout the return period by $\frac{1}{2}C$. and if reinforcing tanks to make them effectively resistant to earthquakes is to be an economical proposition, the reinforcement cost per tank must be less than $0.5C/(N/n)$. For

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* Treated here as the average interval between major earthquakes but see Appendix 4.

example, if N = 25 years* and n = 5 years, the reinforcing system, to be cheaper than doing nothing, must cost less than 10% of the cost of replacing a tank.

An important corollary of this relationship is that *if more money is spent on increasing the life of a tank against corrosion then more may justifiably be spent on making the tank resistant to earthquake shocks.* Furthermore, the increase will be quite sharp since both n and C will have been increased.

Example: Based on estimates from Table 2, the cost of an effective reinforcing system for a CGI tank cannot economically exceed $13.50 when the return period of an earthquake is 25 years. The economically justified step of painting the tank with tar-epoxy increases both life and cost and allows $36.00 to be justifiably spent on strengthening. Clearly this gives the designer more scope to arrive at an effective reinforced system. Carrying this argument further, up to $88 may be allowed for a modification to a conical FRP tank to render it earthquake-proof.

So far the focus has been on the cost of strengthening each tank, a situation which requires the reinforcing system to last no longer than the life of the tank against weathering,

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* Throughout this report the earthquake being considered is deemed to be of such intensity that virtually all CGI tanks are destroyed and it is implicit in the table of Appendix 1 that this intensity is equal to MMVIII or greater. The zone intensity maps given by J.A.Brooks (1) show that most of New Guinea, and all of New Britain, New Ireland and Bougainville lie in a zone for which the return period of earthquakes of intensity VIII (Modified Mercalli) or greater is 25 years.

If a system of considerable durability were devised which could be applied to several replacement tanks in turn, the budget for such a system would be correspondingly higher than the one arrived at above, with the advantage stated previously, viz. that designers would have a better chance of producing a highly effective system for protecting tanks from earthquake damage, simply because the budget will be larger.

If the life of the reinforcement system is T years, and P is the integer equal to or less than T/n (it is necessary here to consider durability in terms of multiples of tank life), then the budget for a re-usable system could economically be 0.5 nCP/N.

In the preceding discussion, the reinforcing system is assumed to be capable of protecting the tank against the accelerations experienced in a shock MMVIII or higher. The "or higher" is a very severe requirement and, statistically speaking, any practical solution will fail sooner or later. Some of the statistical and design implications of the "or higher" phase are discussed in Appendix 4.

Another way of looking at the relationship between the durability of a tank against weathering and its resistance to earthquake damage is that without an adequate ability to withstand seismic shocks the potential life of the tank will not be achieved. The effective life (E) in seismic areas is obtained by dividing the earthquake return period by the number of tanks used in that period.

$$E = N/(N/n + {}^1/_2)$$

where N = return period in years of a damaging earthquake
n = tank life in years against weathering.

The effect of seismicity on tank life may be gauged from the following comparison of weathering life and effective life when N = 25 years.

n	5	10	15	20	25 years
E	4.5	8.3	11.6	14.3	16.7 years

Thus *improvements in life against weathering under non-seismic conditions have to be clearly justified if they are to remain economically viable when the shorter effective life in seismic areas applies.*

The influence of effective life on the cost-in-use of the range of tanks previously considered is also shown in Table 2. This shows the effective life of the tanks for a return period of 25 years for a seismic shock of MMVIII or higher and assumes that all tanks would be damaged equally although reference to the tabulated earthquake resistance indicates that this will not be the case.

6. DESIGN CONSIDERATIONS

"Design" here has two meanings; the detailed treatment of reinforcing systems for tanks, and the overall policy for whole communities or regions.

(a) Design for Earthquake Resistance

There is a strong need for a facility for simulating earthquake accelerations, both to give fuller insight into the mode of failure of tanks and supports, and to provide means of testing reinforcing systems. The accelerations involved should range up to say 0.2 g.

It is probably premature to consider low-cost reinforcing systems until a study can be made of tank failures, but in the case of CGI tanks, floating and/or fixed baffles or greater venting of the tank top may have advantage. Various methods have been proposed for stiffening the tank, but the most promising is based on a suggestion by Prof.G.W.Housner of California Institute of Technology.who said "I know that during earthquake shaking, the corrugations tend to compress from the bending. The earthquake resistance of the tanks would be much improved, I think, if four vertical steel bars were tackwelded to the outside of the tank so as to provide stiff tendons to resist the bending. I believe that the bars need not extend the full height of the tank, but only the bottom 60% or so".

The welding of bars to tank iron would pose difficulties including that of enhanced corrosion. It is believed that a similar benefit could be obtained by the use of four or more vertical ribs pressed from light plate so as to have a sinuated edge which would engage the corrugations of the tank (Fig. 13). The ribs would be right angled in cross-section, galvanised, and be strapped into place with galvanised fencing wire. The system would be entirely compatible with the tank iron, require no skill in fixing and be capable of transference from a corroded to a new tank.

Another aspect of the problem is the need to devise a system for preventing tanks from overturning without increasing damage to the tank itself e.g. an arrangement of guys attached to a stiffened tank top. Alternatively, it might be possible to design an energy-absorbing mounting system for tanks perhaps incorporating the tank stand itself.

Corrosion of CGI often starts at the joints where the zinc has been disturbed by the rivetting and soldering flux and bursting at the joints is a feature of earthquake damage. Some consideration might therefore be given to joints made with epoxy-resin; this technique is currently used with success on spoutings and down-pipes..

(b) Policy

A "systems approach", based on numerical data, would be desirable here, in order to find the optimum strategy for treating or not treating against corrosion and reinforcing or not reinforcing against earthquakes, using various types in various localities, but it is unrealistic to suppose that there will be sufficient accurate data for such an approach to be feasible. The possibility of reticulated water supplies being provided in the main towns has also to be borne in mind.

A less ambitious approach would be to suggest that costs of proposed treatments and reinforcing methods for domestic tanks be measured against the economic yardsticks discussed in Sections 2 and 5, using cost, lifetime, and seismic risk estimates for two broad categories "Coastal" and "Highlands", whilst suggesting acceptance of whatever it costs to instal and maintain tanks of known earthquake resistance as standby storage for institutions such as hospitals which cannot tolerate interruptions to their water supply. And, since disaster relief organizations would assign these institutions a very high priority, the capacity and hence cost of the tanks need not be particularly large.

7. CONCLUSIONS

Corrosion is the principal agency leading to the replacement of tanks with seismic shock coming a long way behind. It is the sudden and simultaneous failure of many tanks in an area that makes earthquake damage loom so large; a far more widespread and sustained damage goes on all the time through corrosion. If tank life is increased, however, resistance to earthquake forces becomes more important, and the interaction between these two has been developed, to some extent, in Section 5. Criteria have been established for judging treatment or reinforcing proposals. These criteria rely on average data and should be valid in the long run.

It seems clear that the major effort should be directed towards increasing tank life against natural deterioration as even without the effects of earthquakes, the annual cost to Papua New Guinea of maintaining the present stock of water tanks is in the region of $500,000.

The CGI tank, as usually installed, is relatively inexpensive but it has a short life against corrosion and is highly susceptible to damage by earthquake. Simple, cheap treatments to improve the corrosion resistance are commercially available and stiffening or bracing the tank against seismic shock may be economically feasible. Various alternative tanks are available but a lack of data concerning durability and performance during earthquakes precludes a firm recommendation. The overall characteristics of timber and ferrocement may make these materials of particular interest for tank construction in Papua New Guinea.

It is recommended that data should be gathered on the earthquake behaviour of tanks and supports, and that simulation of earthquake shocks should be pursued in the hope that simple and inexpensive modifications of ordinary CGI tanks, and/or the supporting structure might be found, in which case large scale losses of tanks and stands in a severe earthquake could be averted by their general adoption.

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APPENDIX 1 : ADAPTED M.M. INTENSITY SCALE

The table reproduced on the next page and prepared by the Geophysical Observatory, Port Moresby, is an adaption of the Modified Mercalli scale of earthquake intensities. The usual tabulation of M.M. intensities includes allusions to objects not seen in PNG (viz. chimneys, railway lines): these have been omitted and the behaviour of water in tanks and damage to tanks included.

EARTHQUAKES

TABLE FOR EVALUATION OF INTENSITY

EFFECT	M.M. INTENSITY					
	III	IV	V	VI	VII	VIII
GROUND MOVEMENTS	Faint Felt by half population.	Moderate. Felt by most.	Strong Felt by all.	Very strong Slightly affects walking.	Difficult to stand.	People thrown down.
SEEN/HEARD (other sounds apart from rumbling)	Faint rattle of windows, house creaks. Hanging objects swing slightly.	Windows, crockery, etc. rattle, building creaks. Trees shake slightly. Slight sloshing of tank water.	Unstable objects move. Pictures swing. Tree movements obvious. Water sloshes in tanks.	Objects fall, furniture moves. Trees strongly shaken. Water sloshes out from tanks.	Ground waves. Water waves.	Odd trees fall.
AWAKENED	Few	Many	All except few heavy sleepers.	All	All	All
ALARMED	Nil	Very few alarmed.	Few alarmed	Many alarmed, run out of doors.	All alarmed.	Some terrified.
DAMAGE	Nil	Nil	Weaker water tanks leak.	Few water tanks burst. Obvious cracks in weak masonry. A few weak village huts collapse.	Many burst tanks. Unreinforced brick walls collapse. Weaker village huts collapse. Minor damage to house stumps.	Timber framed huts and houses off stumps. Roughly half village huts off stumps or thrown down.
SLUMPING and LANDSLIDES		Rare landslides.	Occasional landslides.	Occasional landslides.	A few landslides. Settlement and cracking of unconsolidated ground.	Extensive landslides. Bad slumping of built up areas. Reef settlement.

APPENDIX 2 : ESTIMATE OF TANKS AT RISK

NUMBER OF HOUSES - EXTRACT FROM SINGLE ENTRY TABULATIONS, PAPUA NEW GUINEA CENSUS, JULY, 1971

Town	Type of Dwelling					
	Rural	High Covenant	Domestic Quarters	Low Covenant	Squatter	Native
Lae	12	1289	919	2503	2714	214
Rabaul	10	1054	731	585	457	57
Wewak	18	276	134	634	277	965
Madang	1	563	243	493	674	509
	41	3182	2027	4215	4122	1745

In estimating the number of tanks associated with the houses in the above Table it was taken that the rural and high covenant dwellings were equipped with two 9000 ℓ (2000 gallon) tanks and the domestic quarters and the low covenant dwellings with a single 9000 ℓ tank. It was assumed that squatter and native houses were not fitted with a tank water supply. On such a basis, the houses considered involve 12,688 tanks.

However, two further factors need to be taken into account in arriving at a fair estimate of the number of water tanks at risk in these towns. On the one hand a certain proportion of the dwellings listed will be part of educational institutions, military establishments etc. and will therefore be connected to a reticulated water system. On the other hand, the tabulation does not include shops, offices, hotels or factories etc., which will all have one or more tanks. In the absence of any data to the contrary, it has been assumed that these two factors offset one another and the estimate of number of tanks rounded off at 12 000.

APPENDIX 3 : STERILISATION OF SURFACE WATER AND A COST COMPARISON WITH STORED WATER

A recommendation for the emergency chlorination of surface water calls for the addition of hypochlorite sufficient to give a free available chlorine residual of 0.2 ppm after a contact period of 20 minutes. It is difficult to give specific dosage levels since the chlorine demand of the water will vary (predominantly with the organic content of the water) but a reasonable starting point is held to be 5 to 10 ppm available chlorine. In situations where the volume of water cannot be measured or estimated, a general rule is to add hypochlorite until a faint taste of chlorine persists.

For emergency use, calcium hypochlorite is a convenient source of chlorine, being a dry powder: it is rated as containing 70% available chlorine and costs in the region of $60 per 50 kilogram. Dosage for 10 ppm available chlorine addition requires 12 g/1000 ℓ (2 oz/1000 gallons) giving a material cost of 1.4 cents/1000 ℓ (6 cents/1000 gallons).

Papua New Guinea has a high rainfall and most towns have access to a river, spring, or artesian water bore. There is general belief among civil defence and public health officers that satisfactory supplies of water could be drawn in emergency from these sources using tankers fitted with motor driven pumps - these trucks are available from fire-fighting services and construction authorities or companies in most towns and centres.

It is recognised that access to emergency water may be difficult for some little time after an earthquake because of the condition of roads and bridges but again road-making equipment is available in most areas.

Assuming that tankers can be requisitioned in an emergency, the following figures indicate that pumped water would be appreciably cheaper than water from an emergency tank:

(a) Pumped water

Hire of truck and pump	$30/day
Petrol etc.	$10
Calcium hypochlorite	$ 2
Labour (3 men at $1/hour)	$24
	$66

Assuming cartage of 45 000 litres/day (10,000 gallons/day), cost would be $1.50/1000 litres ($7/1000 gallons).

(b) Stored water

Judging from the figures of Table 2 storage costs in an earthquake-resistant tank are likely to be in the region of $6 per 1000 litres/year ($27 per 1000 gallons/year). It would be reasonable to assume at least 10 years as the interval between withdrawals from the storage and hence cost would be about $60 per 1000 litres ($270 per 1000 gallons).

APPENDIX 4 : STATISTICAL CONSIDERATIONS

The foregoing treatment of justifiable cost increments for effective reinforcement of tanks (Section 3) has been based on a simplified view of seismic risks; viz. that for much of PNG, on average, an earthquake of intensity VIII or higher on the Modified Mercalli (MM) Scale will occur once in 25 years (the "return period"); that there will be on average an interval of 25 years between major earthquakes.

Of course no one expects such events to occur with clockwork regularity every 25 years, and in fact it can be shown* that in any given 25-year period there is a 37% chance that an earthquake of intensity VIII or higher will not occur at all. On the other hand there is a 50% chance that such an earthquake will take place within the first 17 years. It is only on average that the interval will be 25 years.

The use, in Section 3, of the concept of an average interval of 25 years remains valid, but it is essential for designers of earthquake-resistant water tanks to realize that the event being considered is an earthquake of intensity VIII or higher, that is to say, there is a definite probability that a shock of intensity greater than VIII will occur in any given 25 year period. Indeed, if a tank were reinforced to the extent that it would be just capable of withstanding an intensity VIII shock, the probability of failure during

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*See, for example, "Extreme wind gust in Australia", H.W.Whittingham, Bureau of Meteorology Bulletin No.46,1964. Whittingham discusses the Gumbel distribution for extreme values obtained from a large number of years of record. It is assumed in this Appendix that earthquake intensity statistics fits a distribution of that type.

the return period would be 63%!

The accelerations to which water tanks would be subject during an earthquake of given intensity are not known with sufficient accuracy to allow confidence that a given reinforcing system will withstand a given earthquake, but it is instructive to note the magnitude of the "design return period" (and hence design earthquake intensity) required in order that a desired lifetime be achieved with a given calculated risk.

DESIGN RETURN PERIOD FOR VARIOUS CALCULATED RISKS
AND DESIRED LIFETIMES*

Desired Life (yr)	Calculated Risk								
	0.632	0.500	0.400	0.333	0.300	0.250	0.200	0.100	0.050
2	3	3	4	5	6	7	9	20	40
10	11	15	20	25	29	35	45	95	196
20	20	29	39	49	56	69	90	190	390
50	50	72	98	124	140	173	224	475	975
100	100	144	196	247	280	345	448	949	1950

Example: A water tank has a life against corrosion of 20 years and is to be installed in Lae which is in a zone subject to shocks of intensity VIII or higher with a return period of 25 years. To give the tank an 80% chance of withstanding whatever earthquake might occur during its 20 year life it would have to be designed for an earthquake intensity that would occur once in 90 years, namely intensity X.

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* loc.cit. p.14

Similarly, tanks installed in regions falling outside that zone should nevertheless be reinforced against an intensity VIII shock, at least, if premature termination of the life against natural weathering is not to occur too often in the long run, always assuming that this can be done within the budget imposed by the cost criteria.

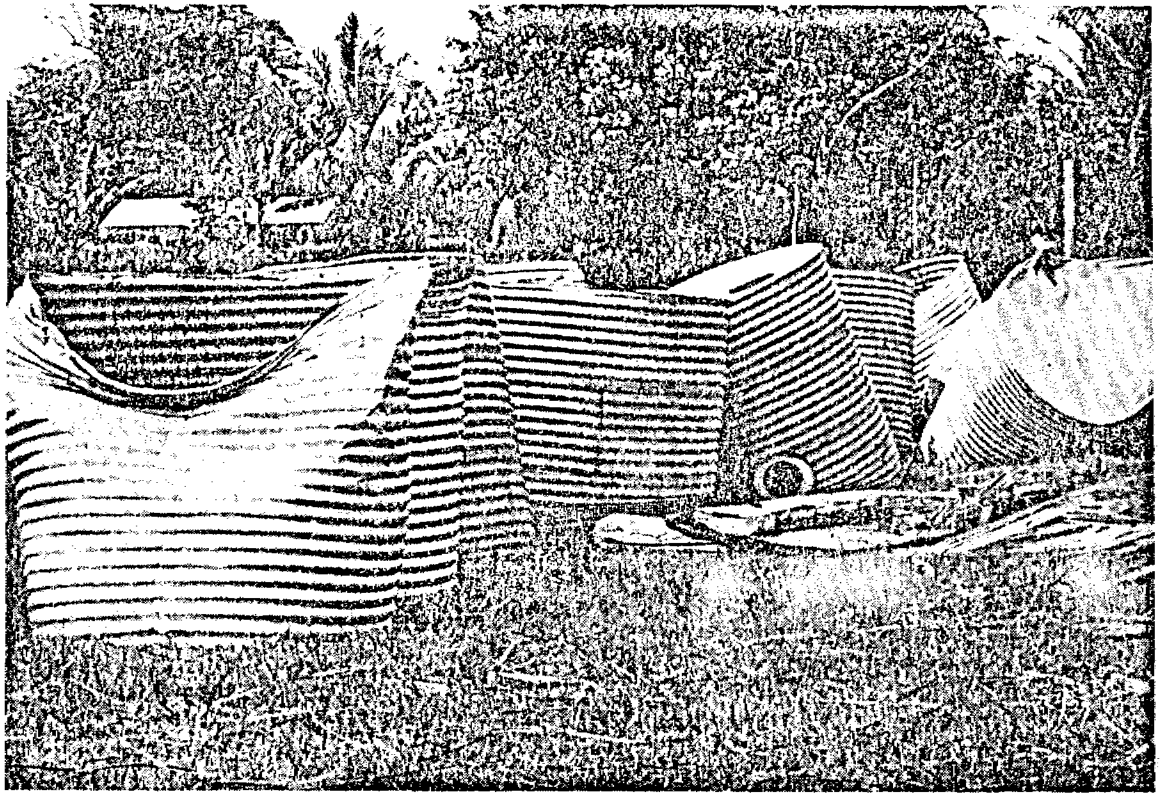


Fig.1 Aftermath of an earthquake: Some of the 12 water tanks ruined at the Bau Vocational School by the Madang Earthquake of November 1970

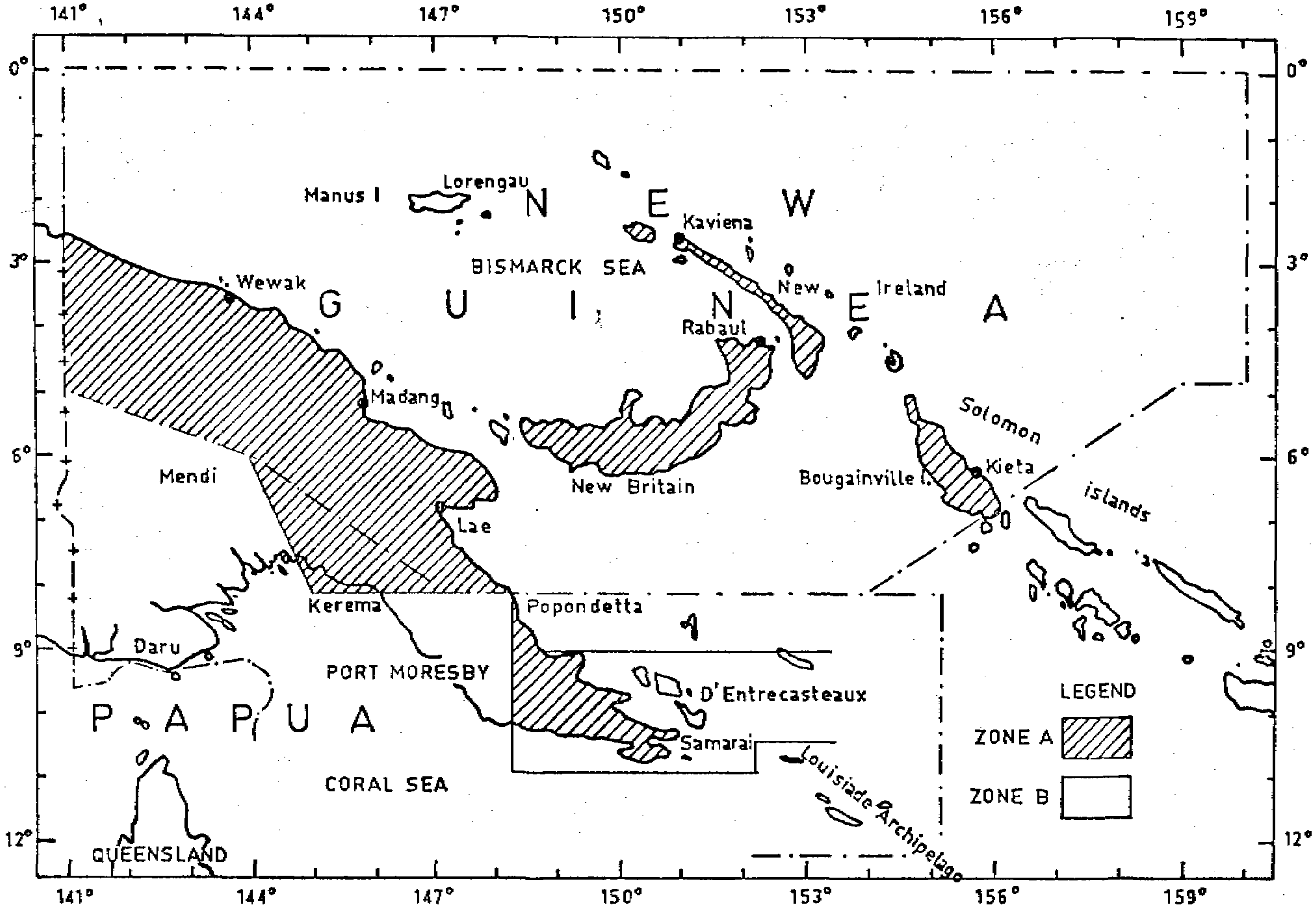
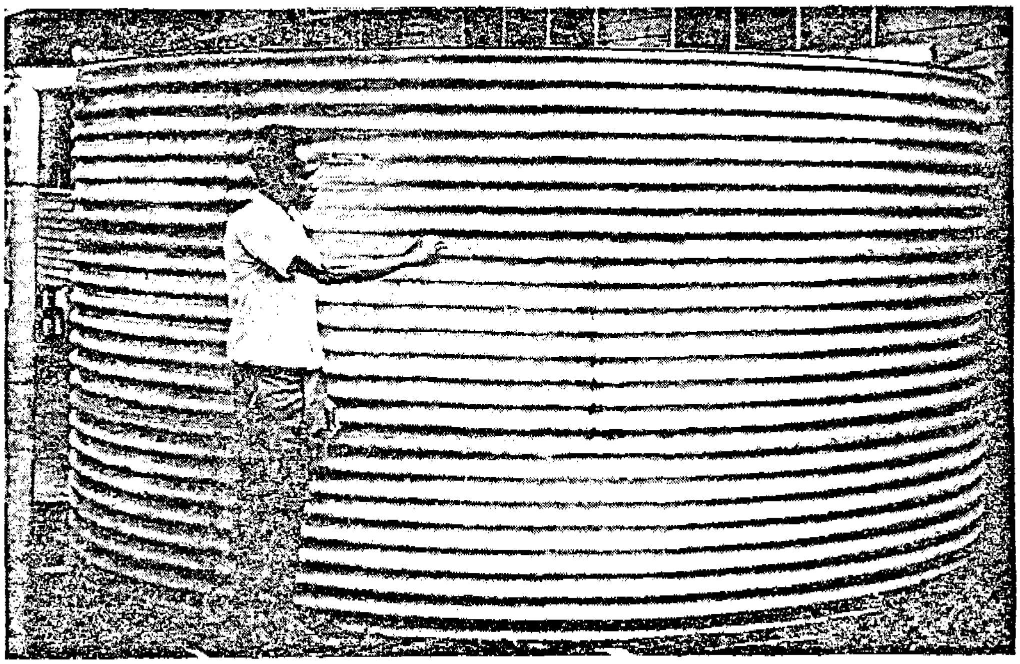


Fig.2 Papua New Guinea seismic zones



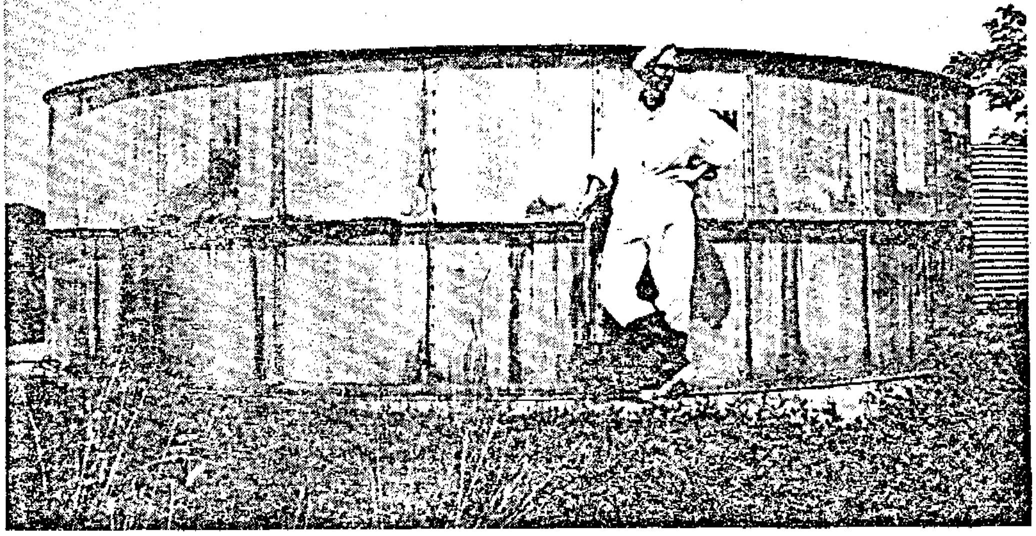
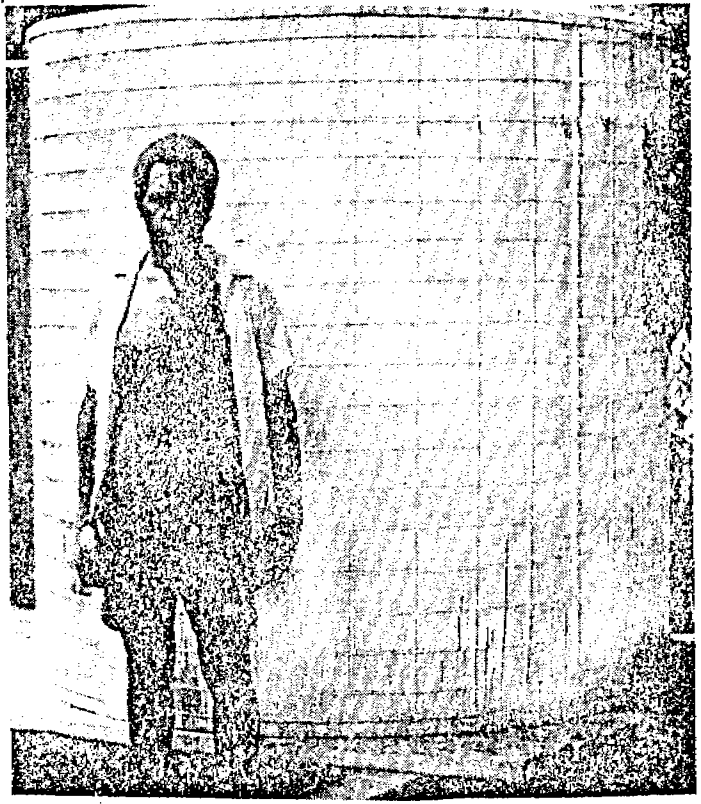


Fig.3 Corrugated galvanised iron tank showing rivet-and-solder join between sheets

Fig.4 Bolted, flat-plate tank of 1.6 mm (16 gauge) galvanised steel



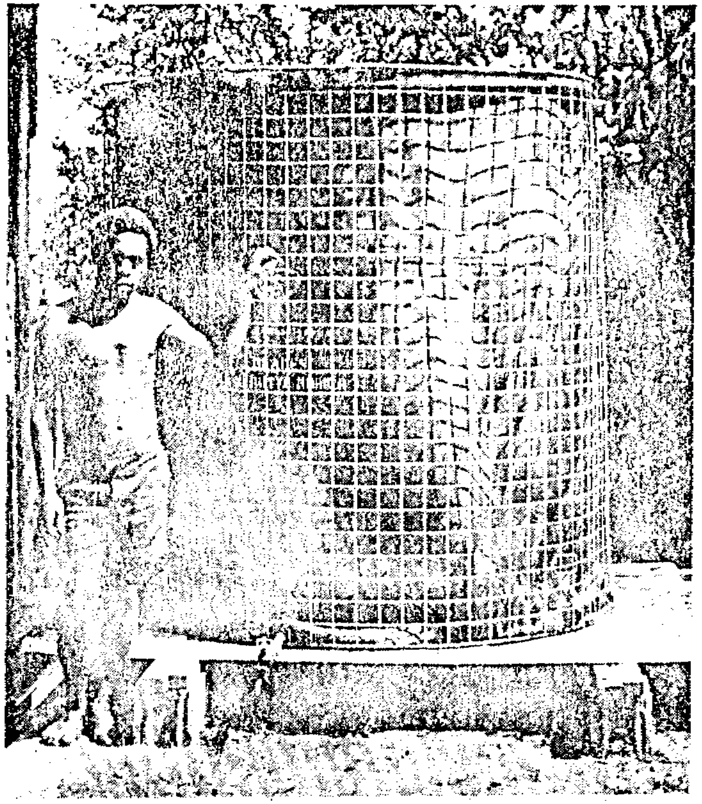
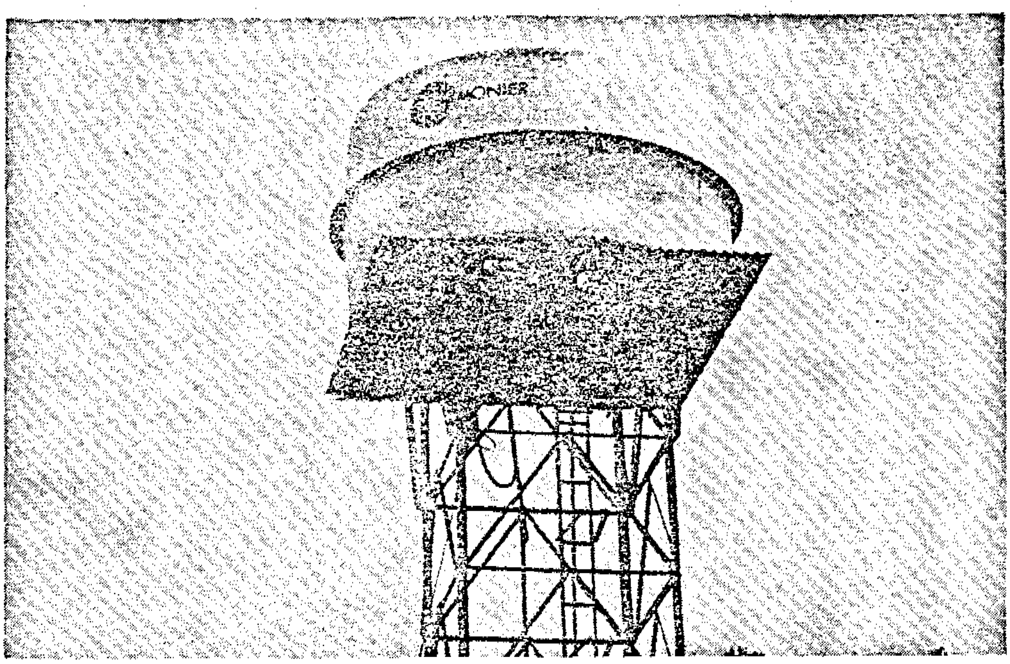


Fig.5 Polyester-glass fibre tank of the type supplied in kit form and cemented up in the field

Fig.6 Butyl rubber membrane tank showing method of support by galvanised steel mesh cage



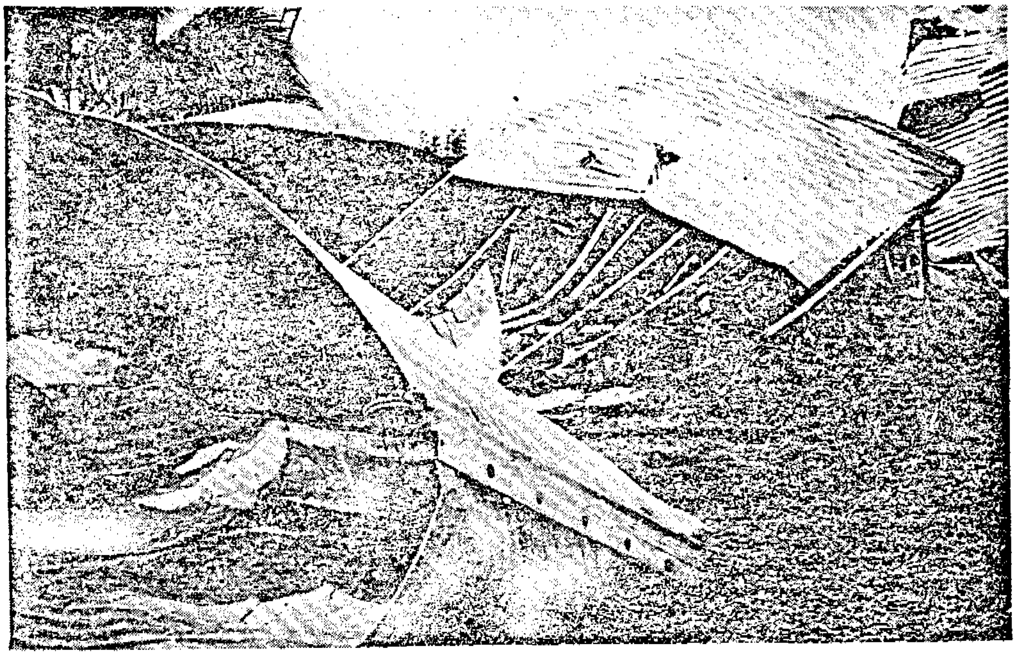


Fig.7 Polyester-glass fibre tank formed by bolting together two conical, nesting halves

Fig.8 Tank damage at Malabunga High School (near Rabaul) following collapse of a steel tank stand during the North Solomon Sea Earthquakes of July 1971

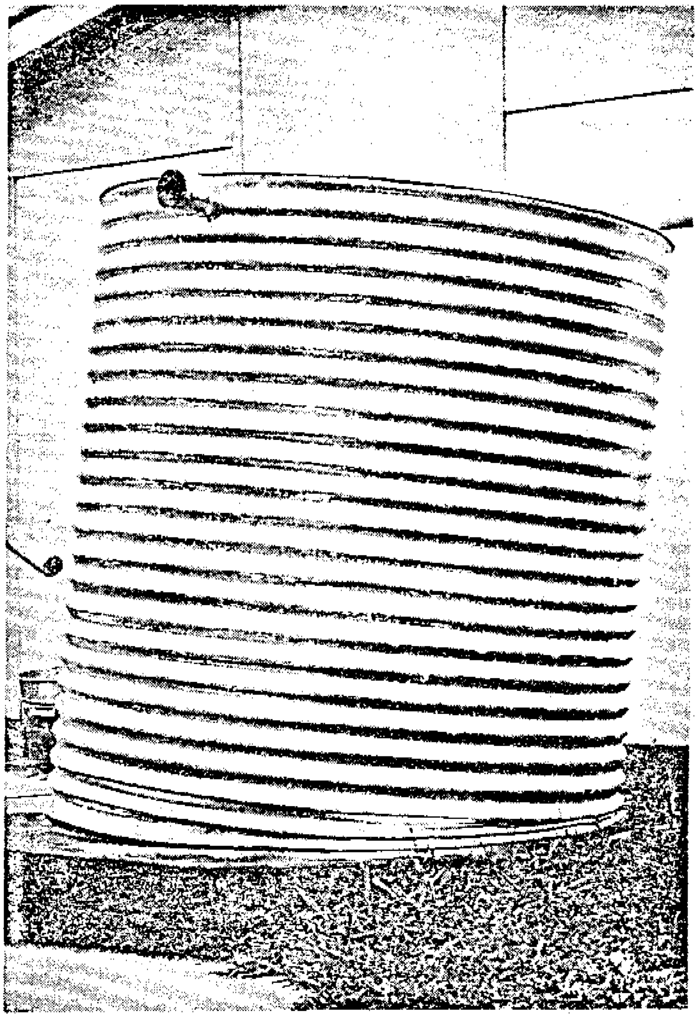
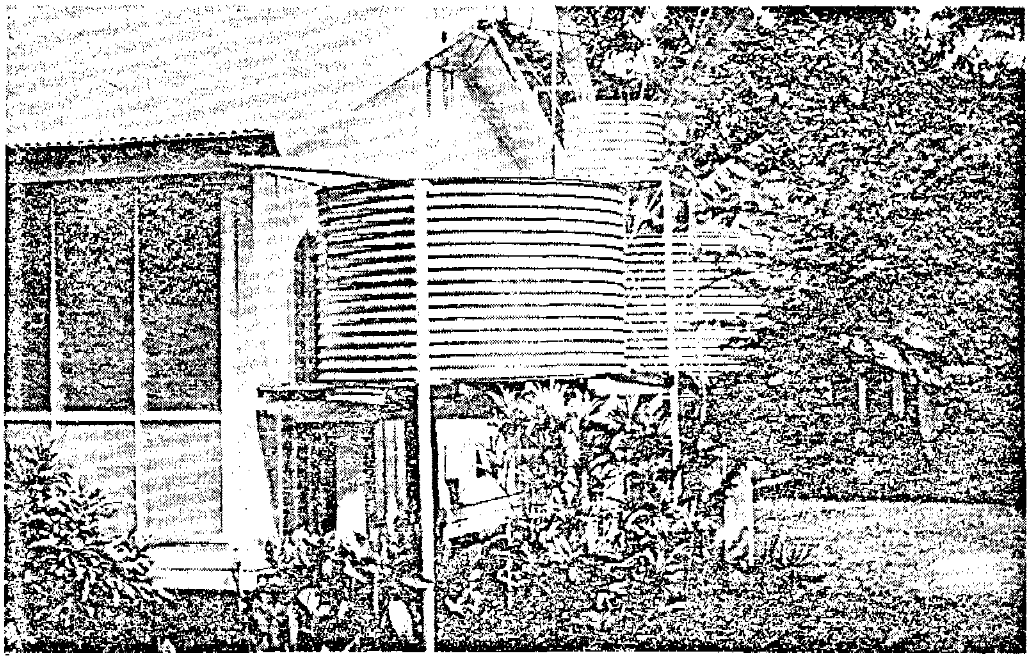


Fig.9 Failure of a CGI tank by collapse of the corrugations



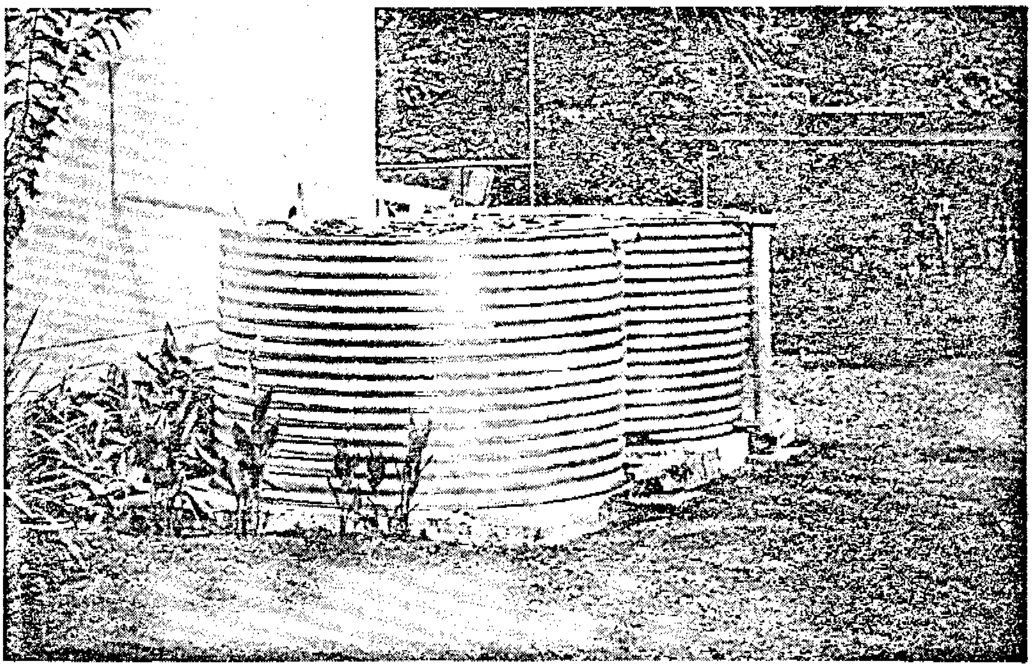


Fig.10 Elevated tank installation at Lae. Supply of water to the house is by gravity.

Fig.11 Domestic water supply by electric pressure pump from tanks on a concrete pad

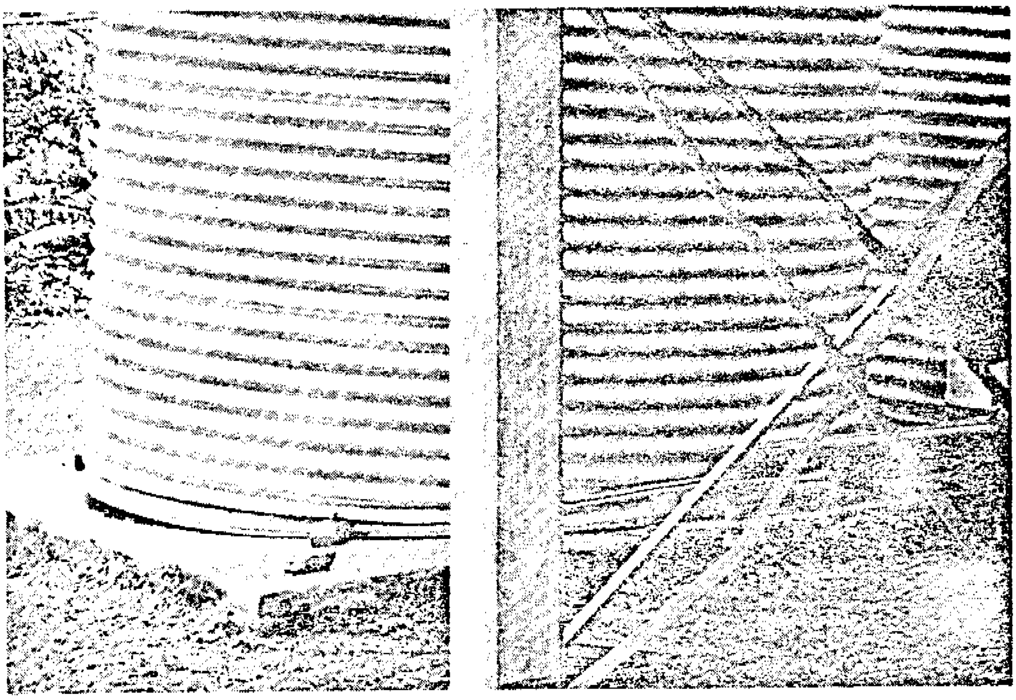


Fig.12 Example of domestic water tank fastened to the concrete base pad by wooden cleats. "Concertina" collapse of the corrugations is visible adjacent to the outlet pipe and tearing or splitting of the tank occurred on the opposite side where restrained by the cleats

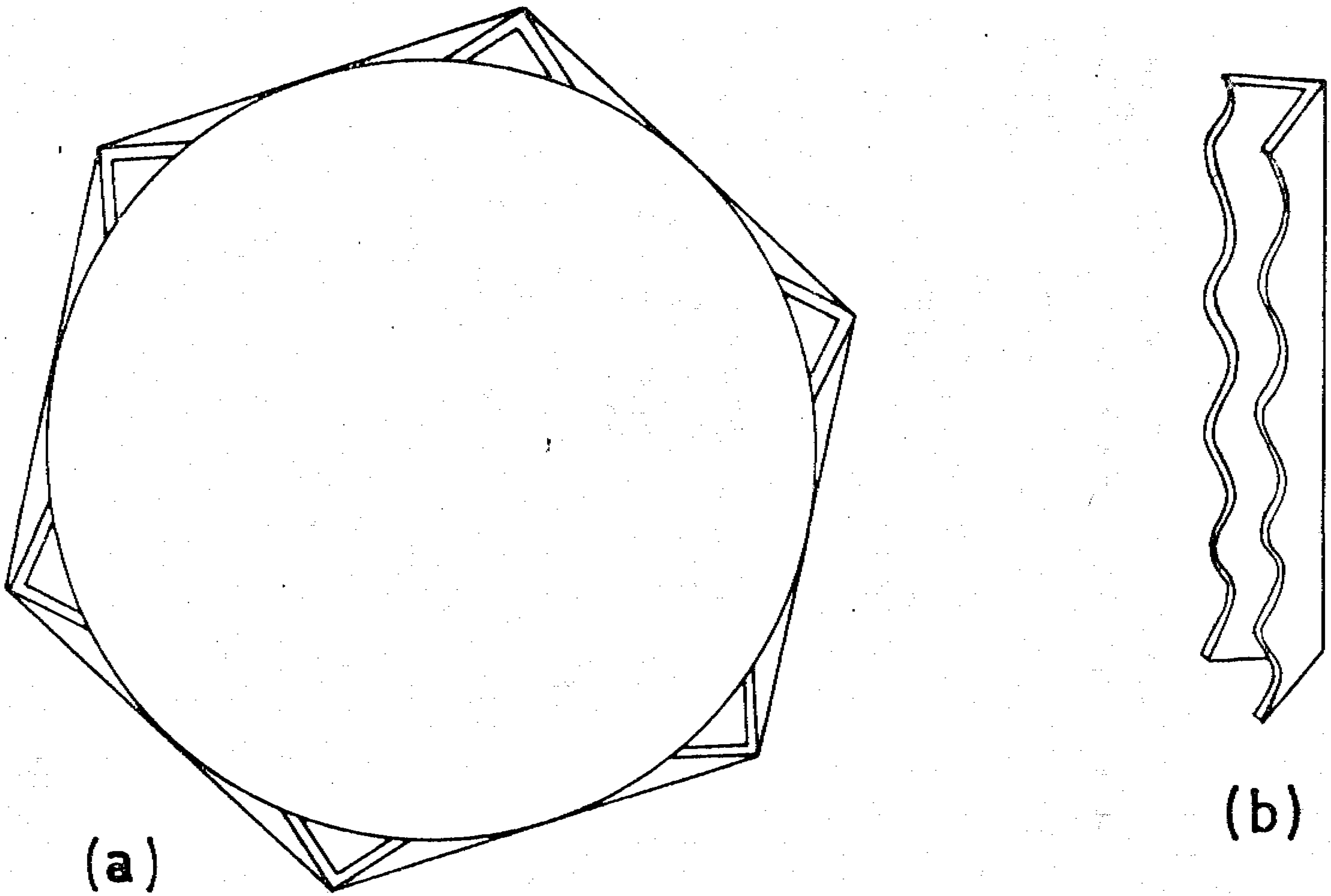


Fig.13 Suggestion for stiffening ribs for a CGI tank