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PROBABILITY AND RECURRENCE OF TROPICAL CYCLONES IN WESTERN SAMOA

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SUMMARY

This report presents a detailed analysis of the probability for and the recurrence of tropical cyclones of varying intensity that may impact Western Samoa. The recurrence of gale to major hurricane force winds is estimated for the five degree square of ocean that includes Western Samoa as well the wind speeds that can be expected to reach Western Samoa. The deep-water significant wave height that will result from those winds is estimated, and the recurrence interval for those wave heights predicted. This information is developed for coastal engineering works in the selection of the design maximum wind speed associated with tropical cyclones, and in the selection of design waves for coastal and harbour facilities in Western Samoa.

On average, Western Samoa should experience a cyclone type wind every 8 years or so. There is about a 65 percent probability of a 47 knot wind at Apia in any 10 year period, and a 35 percent probability of a wind greater than 47 knots in that same period, or a 63 knot hurricane force wind in any 17.8 year period. A wind of almost 92 knots can be expected every 100 years on the average.

The information produced in this study is applied to the proposed Central Bank building site on the fill land in Apia Harbour, showing that less than 3 ton armor stone would be needed for the seawall at the site to protect the fill against waves with a 75 year return interval. A storm surge of 2 metres can be expected in that time period. Design information for the protection of Mulinu'u Point is also presented.

INTRODUCTION AND BACKGROUND

Western Samoa was recently hit quite severely by Cyclone Ofa, and as a result, their government is taking additional precautions to ensure that future coastal development will be in suitable sites, that the degree of exposure to cyclones will be known, and that risks will be minimized by use of safe design. They requested this study specifically for the reclaimed area located in Apia Harbour (Figure 1). Existing cyclone analysis for Western Samoa was minimal, and in general unsupported by an adequate data base. Therefore, to evaluate an important site it was necessary to develop basic information which can be applied to the entire Western Samoa area as well as the specific site.

In particular, it was essential to know the probability for Western Samoa to be impacted by cyclones of different intensities, and to estimate the return interval of those events in order to select a design wave for any site along the coast or in the harbours. Some previous work that was of value in this analysis was done for the improvement of Apia Harbour (Raudkivi, 1975; McVerry, 1975; JICA, 1987, and Meredith & Associates, 1990), and for protection of Mulinu'u Point at Apia (Carter, 1987). More classical work that deals with cyclones specifically from the 1800's as well as during this century was also available (Visher, 1925 and Hutchings, 1953). In particular, the recent observations made by the New Zealand, Fiji, Western Samoa, and Australia Meteorological Services were most valuable in development of the baseline information regarding wind speeds, cyclone speeds, minimum barometric pressures, and cyclone tracks.

Objectives

The objectives of the study were to develop baseline data regarding the probability for and the recurrence of tropical cyclones that could impact Western Samoa including the maximum wind speed, minimum barometric pressure, duration of storm, and resulting significant wave heights. This information is useful in assessment of the potential wave damage, flooding, and wind damage that can be expected within a given period of time at different locations along the exposed shoreline and within the harbours of Western Samoa. Selection of appropriate design parameters is facilitated where such information is available. Other objectives included application of the information developed for Western Samoa to the specific site requested by the Government of Western Samoa.

This study was undertaken as part of the SOPAC Coastal and Nearshore Programme and contributes to Western Samoa country projects WS.5 (Baseline Studies of Inshore Areas to Assist with Coastal Zone Management) and WS.13 (Geological Hazards). The study is especially relevant to Task 90.WS.13a - Baseline study of Mulinu'u Peninsula for management of coastal erosion - requested at the SOPAC 18th Session, in October 1990, by Western Samoa.

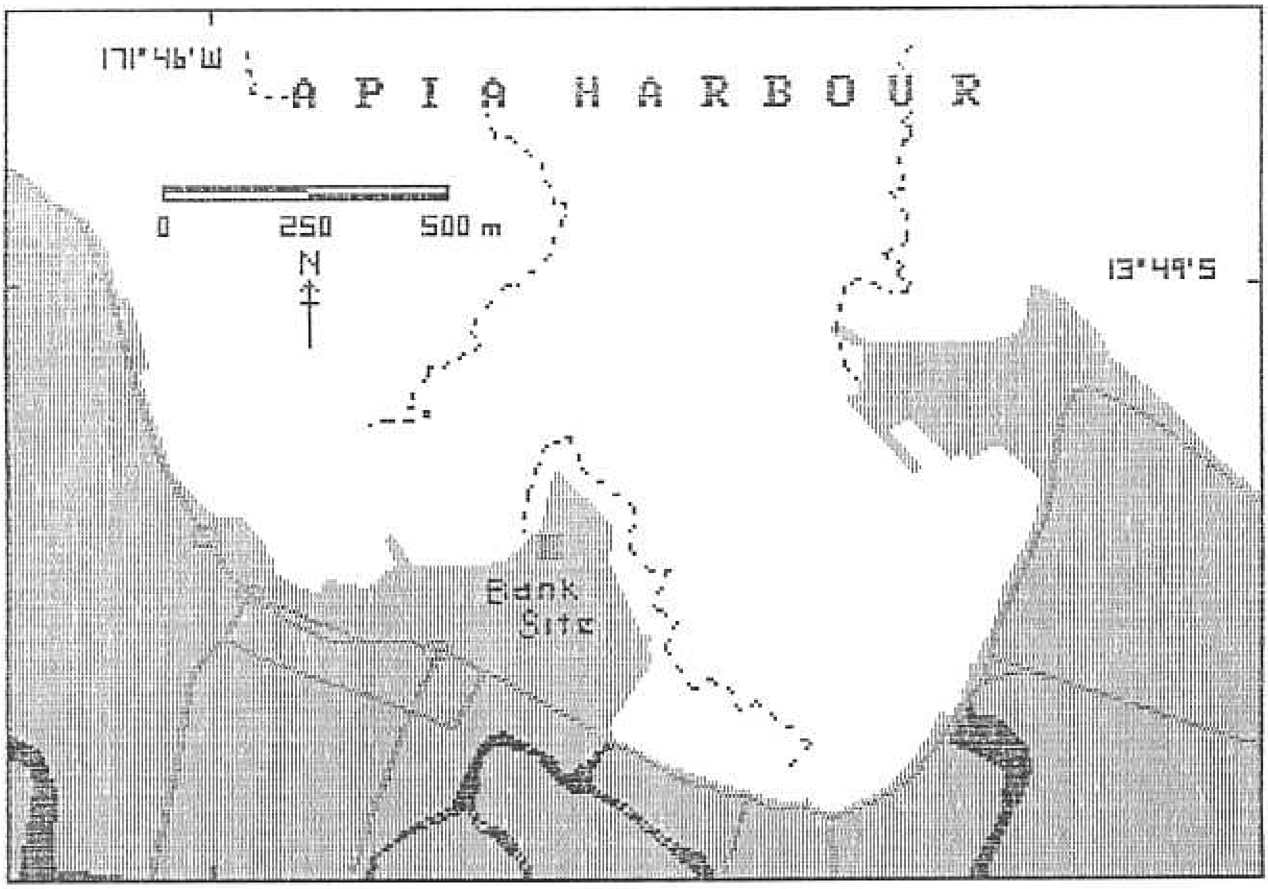

Figure 1. General location map showing the proposed Central Bank building site on the fill area in Apia Harbour. The reefs are shown with dashed lines.

Study Methods

This study was primarily an office exercise, where standard engineering procedures were used for data analysis and presentation. A literature search was made on hurricanes of the South Pacific and of Western Samoa in particular. However, the author did visit Western Samoa 16 to 23 March following Cyclone Ofa which occurred 2 to 4 February 1990. The purpose of the visit was to get first-hand information regarding the hurricane and to draft an engineering report (Carter, 1990) relating to the proposed building site on the filled area within Apia Harbour.

The last ten years of hurricane track data were received from the Fiji Meteorological Service (Krishna, 1990) in Nadi and these satellite data were compared with the previous ten years of satellite hurricane track data published by the New Zealand Meteorological Department (Revell, 1981). The wind data accumulated at the Apia Observatory (Saifaleupolu, 1982) were also analysed to develop the return pattern of wind speed at Apia.

Wind data collected between 1951 and 1970 were summarized by the Meteorological Office in Apia (Department Report 1974). The mean hourly wind speed every third hour is recorded from a Dines Pressure Tube Anemometer operated at Mulinu'u. The anemometer head is 80 feet above ground level. The frequency for wind speeds from calm to greater than 40 knots were calculated and these data show that a wind speed of greater than 40 knots will have a recurrence interval of about 5.5 years. These data are of little use in evaluation of hurricane wind speeds at Apia itself, but the recurrence interval appears to be correct for Western Samoa.

The 40 years of data used to calculate the Western Samoa curve in Figure 2 were compiled at the Western Samoa Meteorological Office (Saifaleupolu, 1982). These data are a listing of the annual maximum sustained wind speed observed. During this period there were five occasions when more than one extreme wind occurred during the same year (Pauga and Lefale, 1988). When this happened the additional events had not been included in the 40 year record. The additional event was generally less than 34 knots, but in 1941 there were three events, one with winds of about 73 knots (included in the records) and two with winds of less then 47 knots. Five events, the latter two 47 knot events and three <34 knot events, were added to the 40 year list for the analysis given here. Other values could not be identified.

A statistical method developed by the US Army (Beard, 1952) has been used quite successfully for small samples (20 to 40 years of records) by engineers to predict recurrence intervals for extreme events. Probabilities and recurrence intervals are:

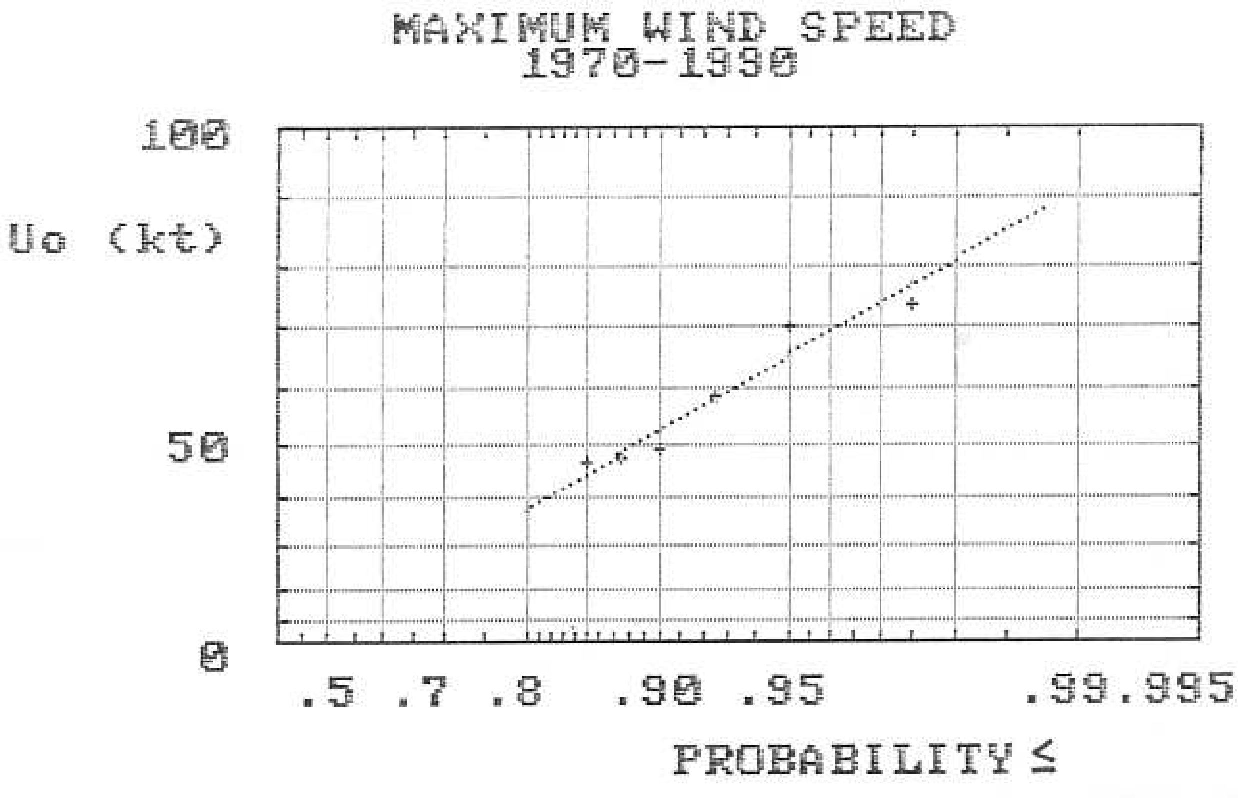

Figure 2. Probability for a given maximum sustained wind speed at 10 metres elevation from 40 years of observations made at Mulinu'u Point.

$$P = 100 \times (SI/(Sn+1)) \quad (1)$$

$$RI = 100/(100 - P) \quad (2)$$

where P is probability, Si is summation of occurrences, beginning with the lowest value to any successive higher value until Si = Sn, and RI is the return interval in years. The probability for the smallest and largest event are often distorted due to the value "1" not being insignificant with respect to the value of Sn.

The probability and recurrence calculated above often plot as a straight line on standard Gumbel skewed distribution paper where P = Exp (-e) and y = (-1n x (-1n(P)). It is generally to advantage to have the data plot in a straight line, so that projections can be made with greater confidence than with the scattered data plotted in a curve. When the Gumbel approach fails the data may plot as a straight line on arithmetic probability, log-probability, log-log, power-probability or power-log paper. The number of significant figures given for the factors may appear excessive in some instances with respect to the data given, but this is necessary for the curves to be reproducible.

Where track lines were available, the average forward speed of the cyclone was determined for the duration of maximum wind speed. The wind speed considered during analysis of five degree crossings (5 degrees latitude and longitude or an area of ocean approximately 300 x 300 nautical miles) was that for the cyclone while it was close to Western Samoa, even where the maximum wind speed became much greater as the cyclone proceeded away from Western Samoa.

The values for the paired wind speed and barometric pressure were used as reported in the records, but they do not necessarily represent maximum and minimum values. Wind speeds were corrected to 10 metres elevation either for over water or over land as needed in the analysis. Maximum wind speed is the average maximum 10 minute sustained wind speed. Gusts are not in general significant for estimation of the significant wave height (significant wave height, Ho is the average wave height of the larger 1/3 of the wave heights that are present in the wave field). Most wind records were reported in Beaufort scale or knots. These values were used in the analysis.

	Equivalent speed range		
Beaufort scale description	kts	m/s	km/h
Below gale up to force 7	<34	<17.2	<62
Gale, force 8 to 9	34-47	17.2-24.4	62-88
Storm, force 10 to 11	48-63	24.5-32.6	89-117
Hurricane, force 12	>63	>32.6	>117
Major hurricane	>90	>46.3	>167

The correction for the height of the anemometer used was:

$$Uz/Us = In(Z/Zo)/1n(10/Zo) \qquad (3)$$

where Uz is wind speed at elevation Z, Us = wind speed at 10 meters (30 feet) elevation, Zo is friction length (0.006 metres was used in this analysis), and In is the logarithm to the natural base, e.

Some constants used in this analysis were: 6076 feet per nautical mile, e = 2.718281828 , feet x 0.3048 = metres, 64 lbs per cu ft as the specific weight of sea water, and 32.2 ft per second^2 as the acceleration of gravity.

HISTORY OF CYCLONES IN THE SOUTH PACIFIC

In 1853 Dobson published a list of 24 hurricanes from Pacific island groups. Dobson and several subsequent records were cited in "Tropical Cyclones of the Pacific" (Visher, 1925). Visher lists 325 cyclones passing through the various island groups in the South Pacific. The records include cyclones between 1789 and 1923. Visher recognized that many cyclones were unrecorded if they did not encounter an island group or a vessel. Recent satellite data indicate that there may be about 85 cyclones in the South Pacific in a 10 year period; therefore, as many as 62 percent of the cyclones ocurring during the 1800's may have been unreported, 100x(1-325/850).

Data on tropical cyclones of the Southwest Pacific were summarized by the New Zealand Meterological Service in 1979, and 194 more events were added to the growing list of cyclones (Kerr, 1979). Kerr reviewed the work of Visher, Hutchings, Gavites, Giovannelli and Rotert, Coleman, and others. During and following the Second World War there were sufficient reporting stations to track the progress of some cyclones, and to suggest ways that cyclonic disturbances may develop, including within the intertropical convergence zone, and by wave-like deformation of the normal undisturbed easterly flow (Hutchings, 1953).

Satellite tracking of tropical cyclones was implemented during the 1970-79 decade of recording, and a total of 91 cyclones were observed in the South Pacific area (Revell, 1981). The total number of cyclones reported increased each decade from 58 in the 1940's to 64 in the 1950's 72 in the 1960's, and 91 by the 1970's. Cyclones within the South Pacific area are now tracked by several tracking centers. Fiji Meteorological Service recorded cyclone tracks between 0 and 25 degrees south and 160 degrees east to 140 degrees west until 1988 when they extended the boundary to 120 degrees west. The New Zealand Meteorological Service published cyclone tracks between 5 and 47 degrees south and 145 degrees east to 145 degrees west (Revell, 1981). The Australian Bureau of Meteorology publication “Tropical Cyclones in the Australian Region July 1909 to June 1980 (Lourensz, 1981) covers from 0 to 35 degrees south and 100 to 170 degrees east.

A review of these sources and the data compilation for Western Samoa (Pauga and Lefale, 1988) has resulted in a list of 79 cyclones which have impacted Western Samoa between 1831 and 1990. The records are often brief in the description of the event, and some strong or gusty winds that were not cyclones may have been recorded as such. However, the list indicated that more than 5 events with winds of 30 or more knots wind speed can be expected each decade.

REVIEW AND ANALYSIS OF CYCLONE RECORDS

In general, cyclone information recorded during the last two decades appears to have sufficient detail with adequate coverage to be used to calculate the probability of the occurrence of cyclones of different intensities and return intervals for specific sites. While the 1970-79 data were particularly useful for this purpose (Carter, 1987), it is essential to have the 1980-89 records to compare and develop some estimate of variance. Five decades of satellite data should ideally be available for projections over the economic life of buildings in the South Pacific, which is probably in the order of 75 to 80 years at present. However, by making some assumptions, much of the early cyclone data can be used to support trends or characterestics that appear in the last 20 years of data. These data can be projected to cover 50 to 75 years or so.

Cyclone Recurrence

An example of the application of cyclone records prior to the use of satellites for tracking includes an estimate of the number of cyclones that cross the 5 degree square area in which Western Samoa is located (10 to 15 degrees south and 170 to 175 degrees west). Using data cited above, the following frequencies were estimated

Period	Seasons	Cyclones	Samoa’s 5' sq	#/10 yr	percent+
1831-1932	100	320	23	6.1*	7.19
1939-1969	30	194	19	6.1	9.79
1970-1979	10	91	6	6.0	6.59
1980-1989	10	79**	8	8.0	10.13
		Averages+	6.22	7.87	

\+ The values are weighted for 10 decades, 3 decades, 1 decade etc.
* (850/320) x 23 = 61 or 6.1 per 10 years
** adjust Fiji reporting area to entire South Pacific, 64 x 91/74 = 79

These data suggest that Western Samoa's five degree area is now exposed to about the same number of cyclones each decade as it was during the last century, and that while there may be slight shifts in frequency from decade to decade, the average is about 6, representing about 8 percent of the total cyclone activity in the South Pacific. The previous estimate of >4 events impacting Western Samoa every 10 years appears to support this value.

It is interesting to note that during the 1980's there was a slight shift in the center of cyclone activity toward the east. Tahiti had a significant increase and Vanuatu had a slight decrease in cyclone activity during this decade. It is possible that this shift in the center of cyclone activity was related to an increased effect from the southern oscillation.

Wind Speed Analysis

The wind data recorded at the Apia Observatory provide valuable information on passing cyclones. The 40 years of records for Mulinu'u Point from 1941 to 1981 were compiled by Saifa (1982) and analysed by Carter (1987). These records were reviewed and revised as indicated under Study Methods above and analysed for this study using the Beard method (Beard, 1952). Data for the six events with wind speeds of greater than 47 knots that appear to represent cyclone events were adjusted for elevation and plotted on log-probability paper (Figure 2), giving an estimate of the probability of a given maximum wind speed at that locality.

About 1 in 4 cyclones (Carter, 1987) that pass through the five degree square for Western Samoa produce high winds at Apia, hence only about once in 7 to 8 years will there be a maximum wind speed greater than 30 to 40 knots in Apia.

The six cyclone track records for the 5 degree area of ocean that included Western Samoa for the 1970-1980 period reported by New Zealand Meteorological Service (Revell, 1981) and the nine cyclone track records for the same 5 degree square for the 1980-1990 period reported by the Fiji Meteorological Service (Krishna, 1990) were used to develop the probability for the wind speeds of cyclones crossing the 5 degree square. The Beard method was used to analyse the combined sets of data. The results of the analyses for the 21 seasons are shown in Figure 3, giving the probability for the maximum sustained wind speed.

Using the relationship developed by Beard (1952), the return interval for a given maximum sustained wind speed can be calculated. This was done for the data from Mulinu'u Point (Figure 2), the data for the 15 cyclones crossing the five degree Western Samoa square (Figure 3), and the data

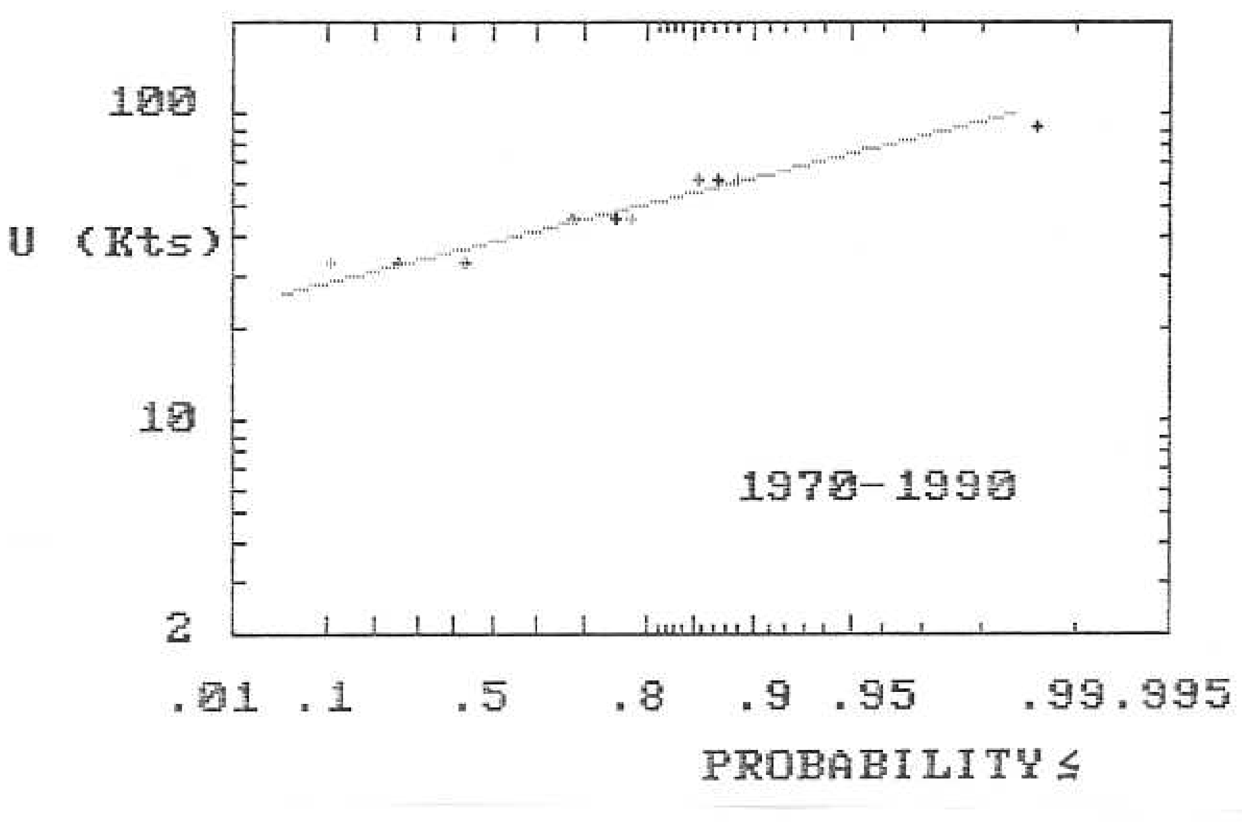

Figure 3. Probability for a given wind speed in a cyclone passing through Samoa's five degree square area during 1970-1990 a total of 15 cyclones were recorded during the period.

for 91 cyclones between 1970 and 1979 in the entire South Pacific. The results are plotted in Figure 4. The expressions for the three lines are:

Apia Wind data:

$$S = 304.904 \times \log(RI) - 50.865 \quad (4)$$

Samoa five degree square data:

$$S = 307.447 \times \log(RI) + 52.775 \quad (5)$$

South Pacific data:

$$S = 451.532 \times \log(RI) + 144.997 \quad (6)$$

where S is wind speed in knots, RI is the return interval in years, and log is to base 10.

The three lines have varying slopes because of the effects of latitude and the longer return interval for the progressively smaller areas. Figure 4 shows that the winds are much stronger at more frequent intervals in the cyclones that cross the 5 degree square than were the winds measured at Apia. Two reasons for this difference are that the same wind over water is about 10 percent higher than when it crossed the shoreline, and that when the cyclone is some distance from Apia only the weaker winds reach Apia. The Western Samoa (WS) curve in Figure 4 indicates a 77 knot wind should occur during the 40 year recording period. A 73.9 knot wind did occur.

Apia Wind Wave Height Return Interval

The six highest sustained wind speeds observed in the 40 years of Apia wind data shown in Figure 2 were used to estimate the return interval for the deep-water significant wave that would be generated over a 36 nautical mile fetch for those winds adjusted for over water at 10 metres elevation (about 10 percent greater than the same wind at 10 metres as it crossed the coast). The values are shown in Figure 5. The expression for the line is:

$$Ho = 73.568 \times \log(RI) - 21.986 \quad (7)$$

where Ho is the deep water significant wave height in ft, RI is the return interval in years, and log is to the base 10.

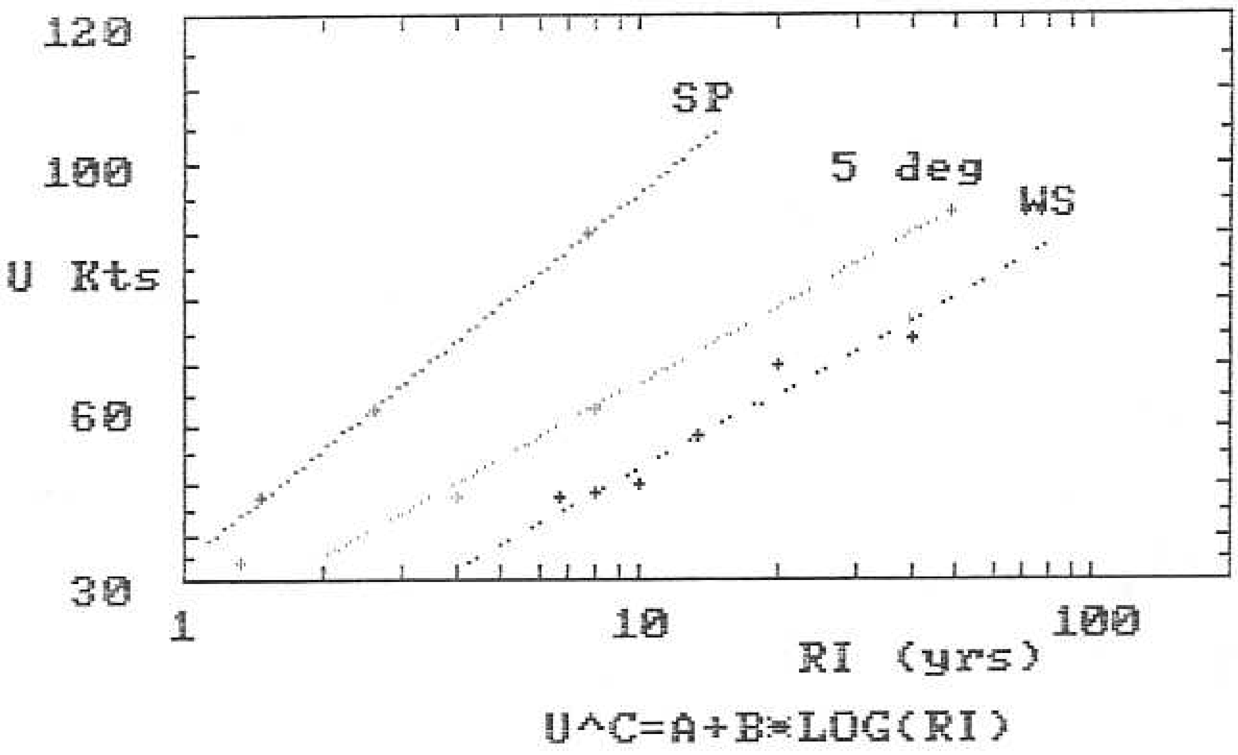

Figure 4. Return interval for given wind speed at Apia, the combined Samoa five degree data 1970-1990, and the wind speed in the 1970-79 South Pacific cyclones.

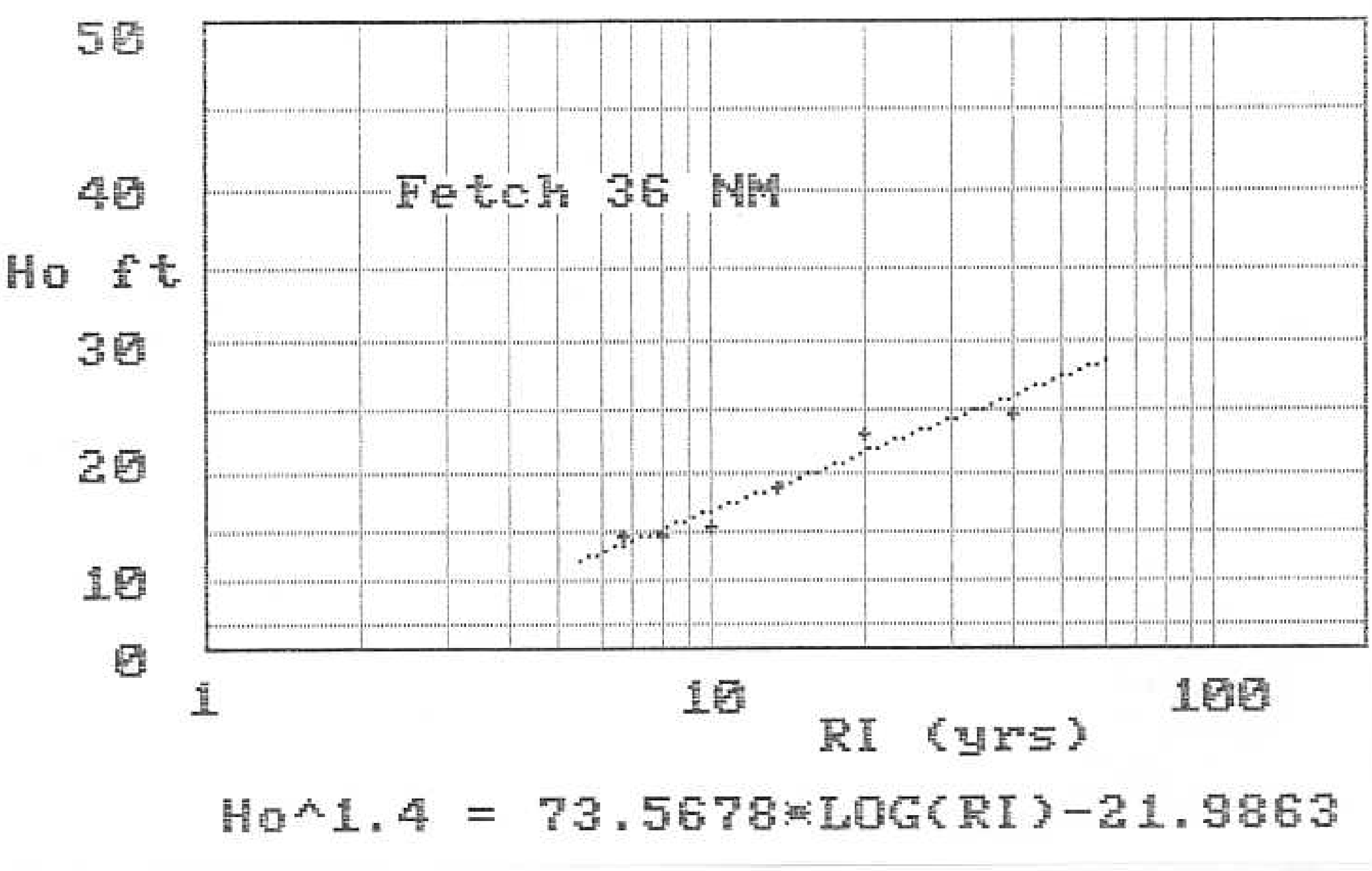

Figure 5. Return interval for given significant wave height estimated from maximum wind speed observations corrected to overwater at 30 feet.

5 Crossing Wave Height Return Interval

The probability for the deep-water significant wave height that will be generated from the maximum sustained wind of a passing cyclone was calculated for an effective fetch of 36 nautical miles (US Corp. 1977. Vol 1 p 3-77.), the value calculated for Cyclone Ofa in 1990. These data are shown in a log-probability plot as a straight line in Figure 6. The return interval for the above significant wave height was calculated, and it plots as a straight line on power-log paper, Figure 7. The expression for the line is:

$$Ho = 64.620x \log(RI) + 2.810 \qquad (8)$$

where Ho is the significant wave height in deep water in feet, RI is the return interval in years, and log is to base 10.

Cyclone Forward Speed

The average storm speed was estimated from the cyclone tracks during the time of maximum wind speed. The cyclones from the Fiji recording area during 1980 to 1989 were used as the data base. The probability for a given average cyclone speed is shown in Figure 8, and the return interval for the cyclone speed is given in Figure 9. The median speed was about 10 knots, and the values vary from almost zero to about 25 knots for the 64 cyclones considered.

Barometric Pressure

Barometric pressure is not always reported for cyclones. In order to find a significant number of observations, it was necessary to consider cyclones from the South Pacific between 1906 and 1990. The reported pressures from 55 cyclones were found to fit a normal probability plot almost as a straight line (Figure 10). It should be noted that the values reported are generally not the minimum barometric pressure at the center of the cyclone, but are likely to be pressures at a random distance from the center of the cyclone as it approached the recording station.

The recurrence interval for observed barometric pressures was calculated, and it is plotted on semi-log paper as a straight line (Figure 11). The 10 year recurrence interval includes pressures greater than 950 mb.

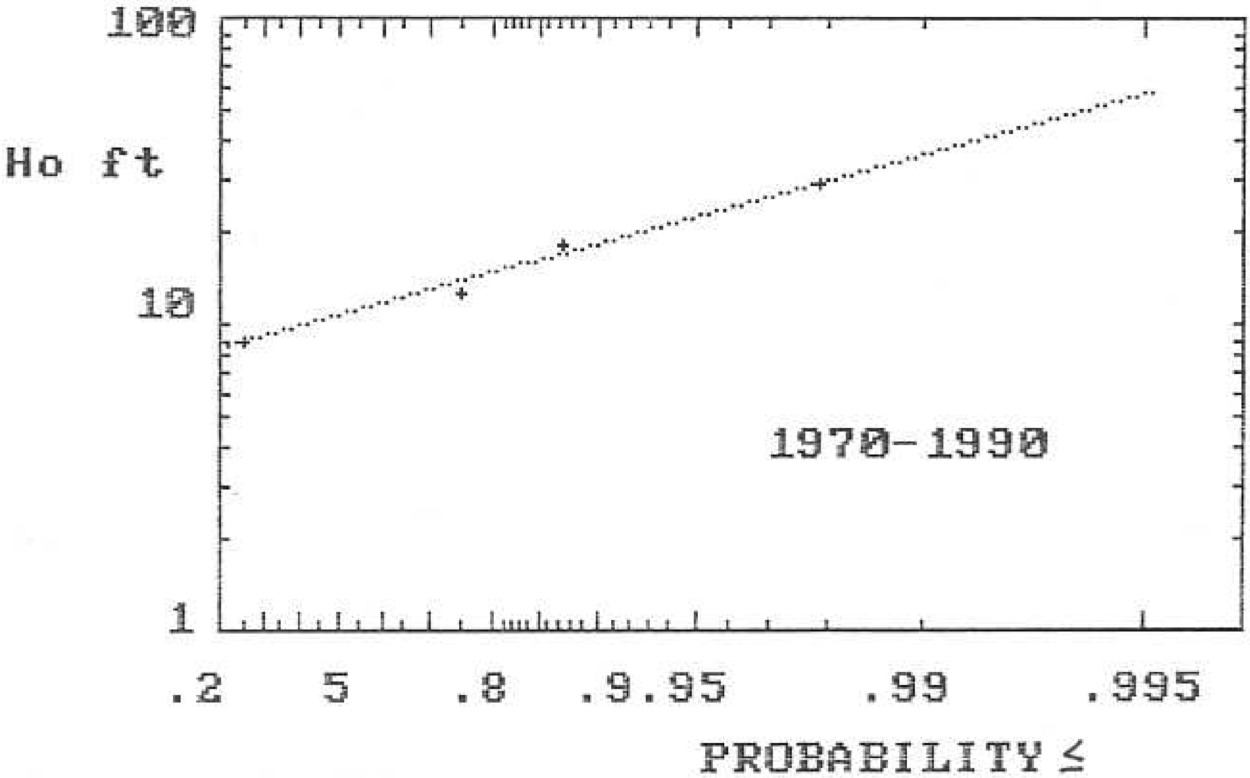

Figure 6. Probability for a given deep water height to occur offshore Western Samoa from the passing of a tropical cyclone.

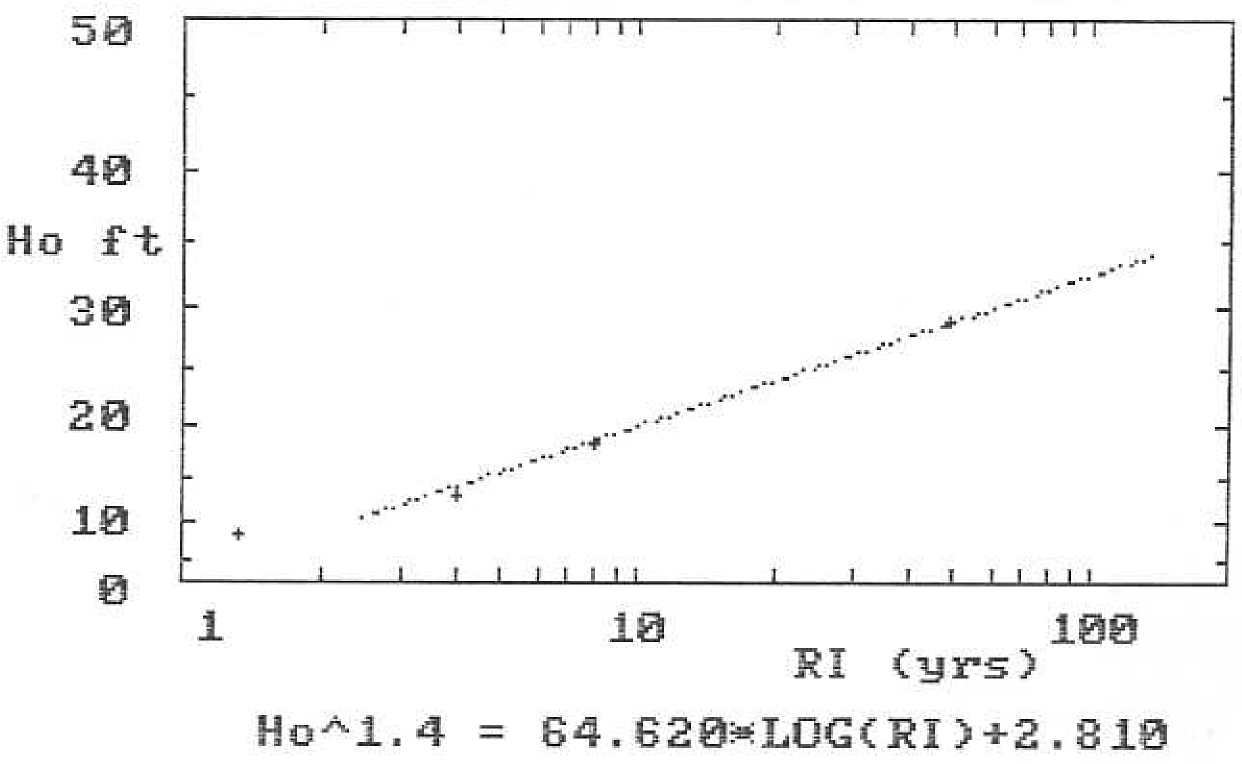

Figure 7. Return interval in years for given deep water wave height offshore Western Samoa due to passing tropical cyclone data taken from 1970-90.

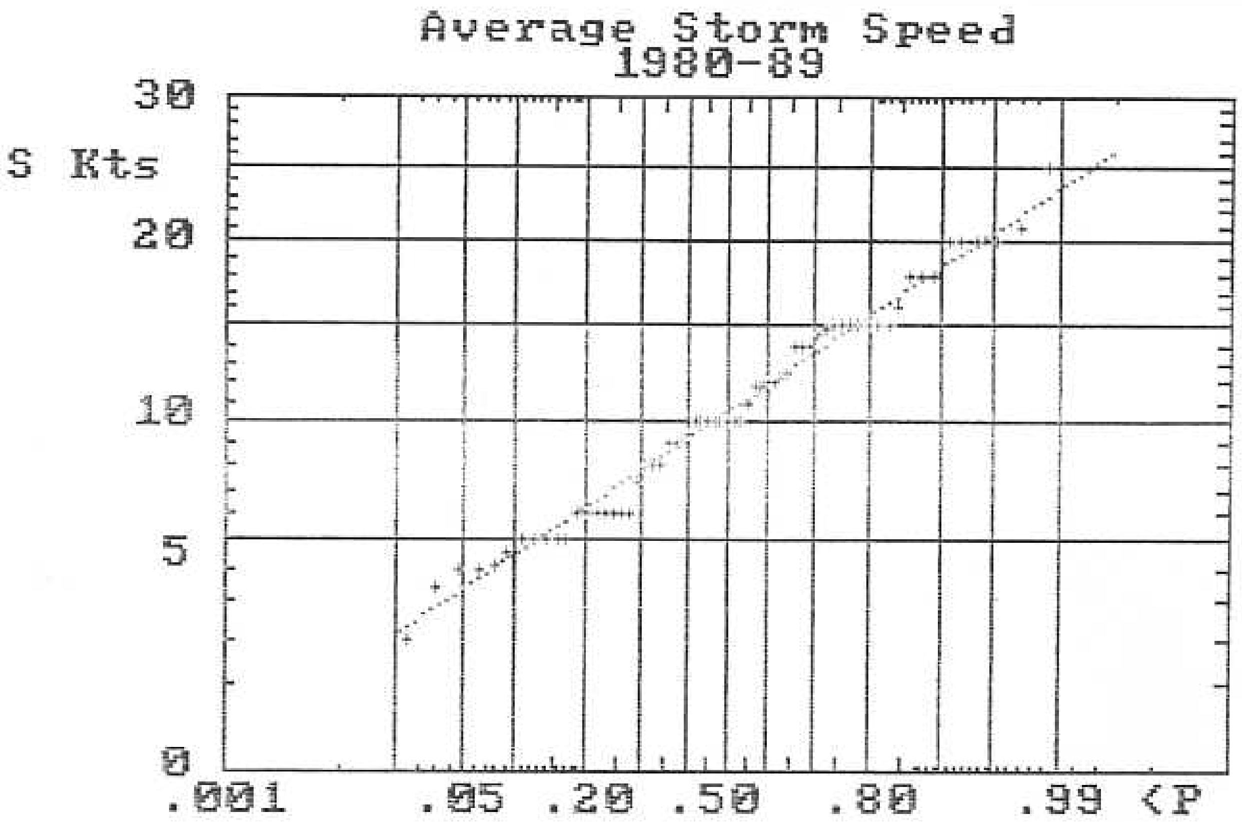

Figure 8. Probability for tropical cyclone average speed in the Fiji reporting area during 1980-1990 when 64 cyclones were tracked and reported.

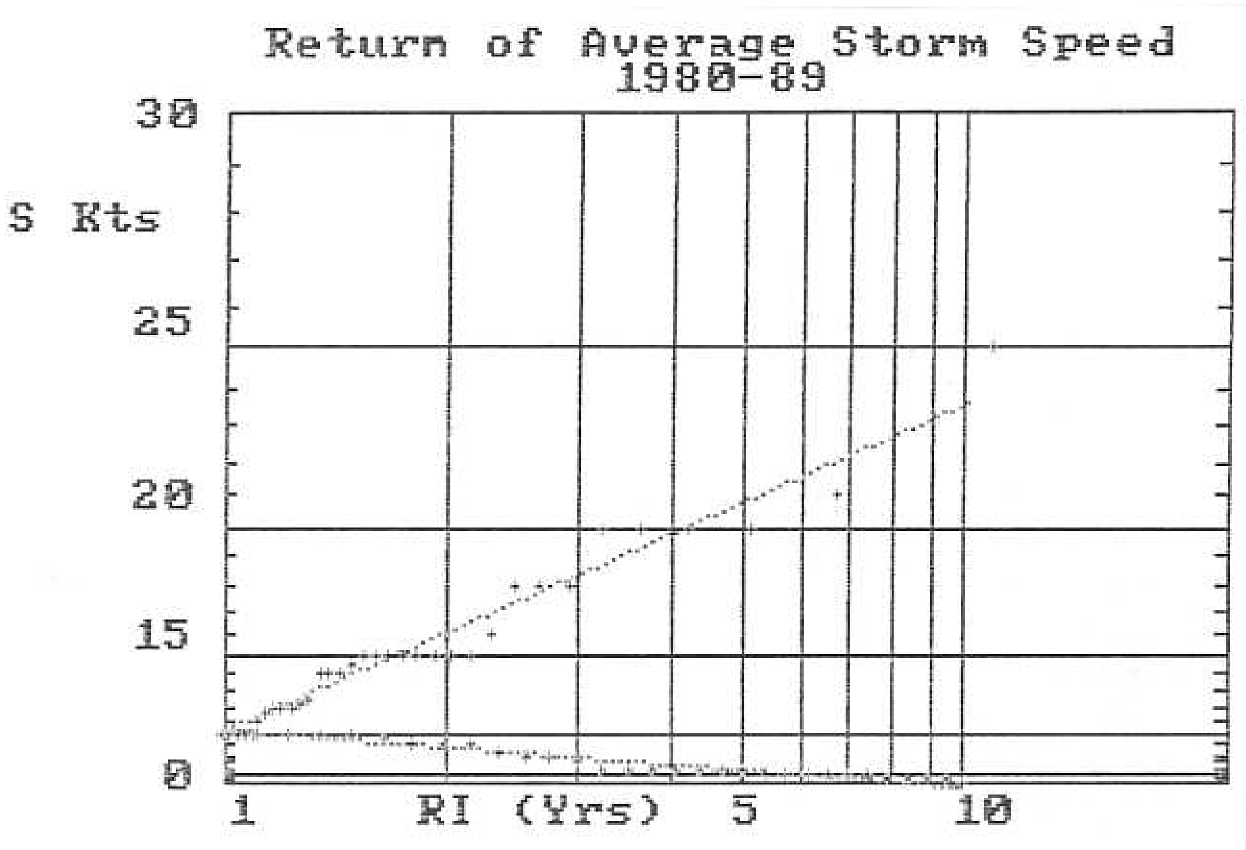

Figure 9. Return interval of a given cyclone average speed in the Fiji reporting area during 1980-1989 when 64 cyclones were tracked.

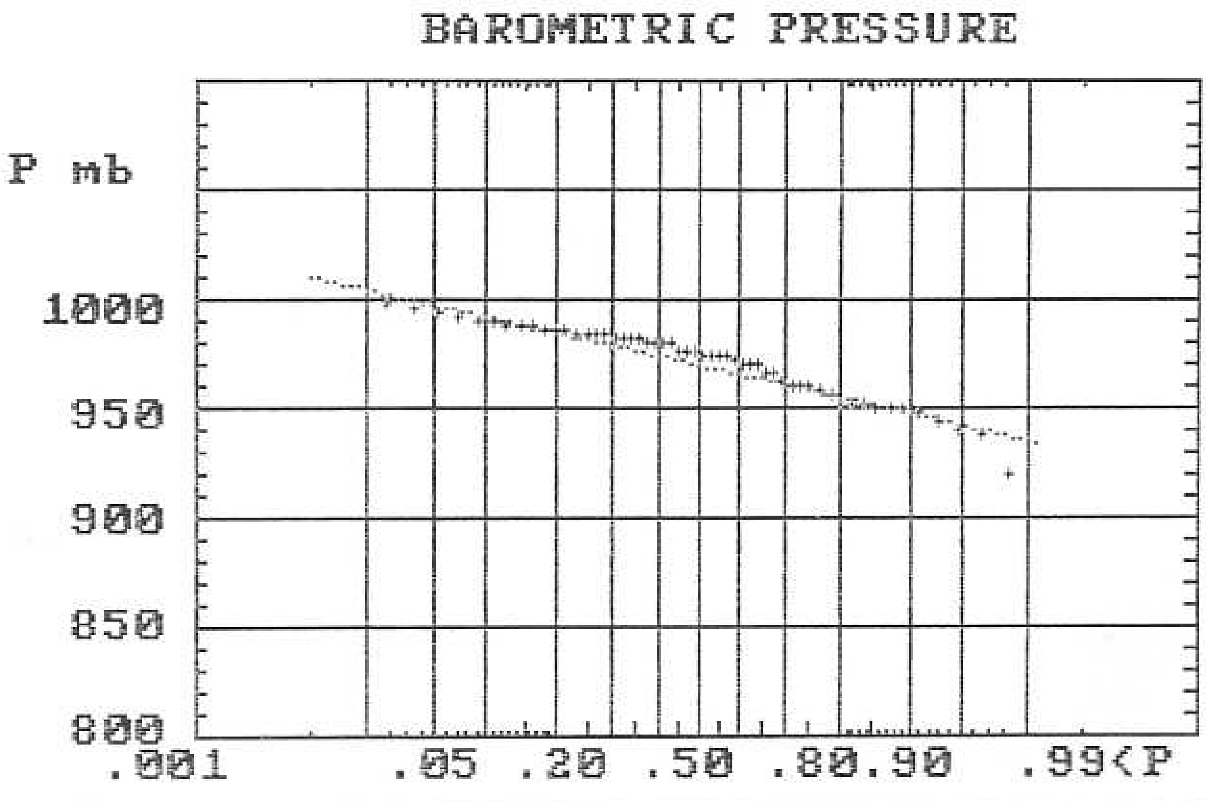

Figure 10. Probability for the minimum reported barometric pressure calculated from 55 South Pacific tropical cyclones observed 1906-1990.

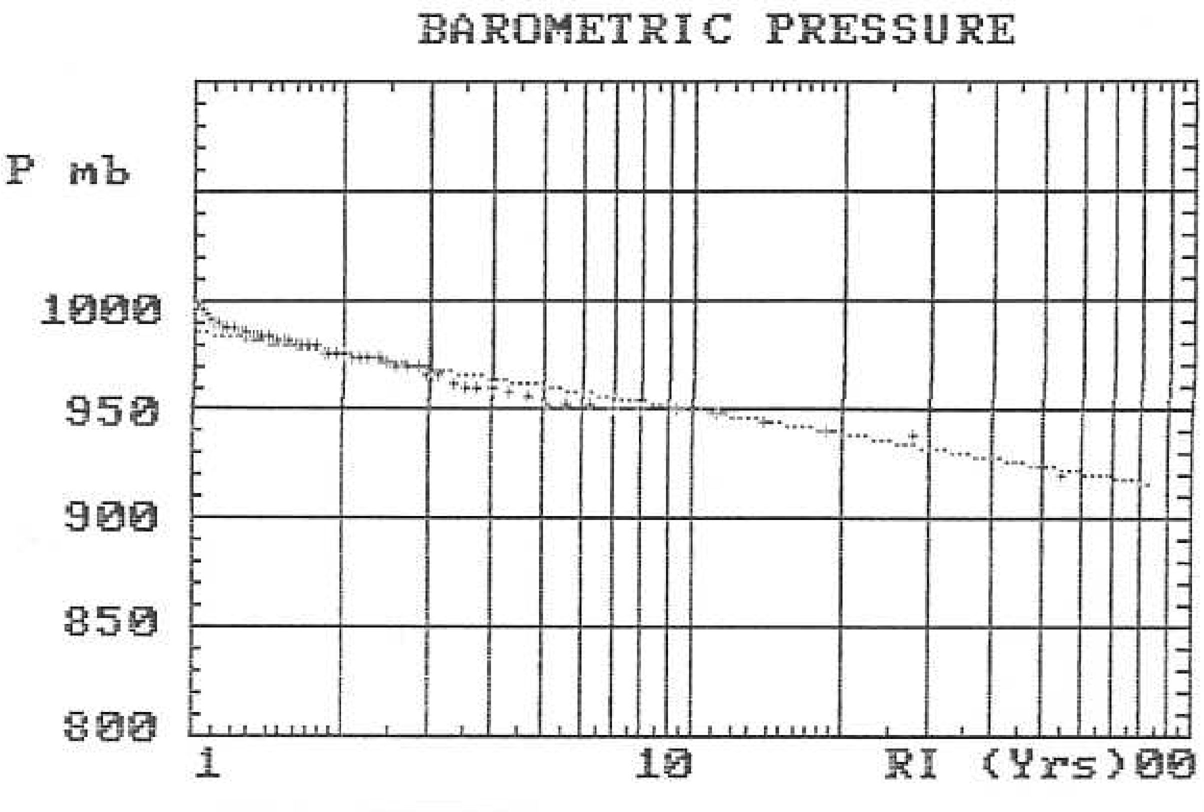

Figure 11. Return interval for reported minimum barometric pressure for 55 South Pacific cyclones 1906-1990. Generally not the minimum Central Pressure of the cyclone.

An estimate of the maximum wind speed is often made from the observed drop in barometric pressure using the following relationship:

$$Um = k(Po-Pm) \qquad (9)$$

where Um is the maximum wind speed in knots, Po and Pm are the barometric pressure at the edge of the cyclone and at the center respectively in mb, and the k is an empirical constant based upon local observations. The value for Po usually varies from 1006 to 1010 mb during the cyclone season in Western Samoa. The average value of k calculated for the 55 cyclones used in Figure 11 was 11.2.

An excellent record of barometric pressure and wind speed was made during the passing of Cyclone Arthur 13-15 January 1981 in Fiji. Seven different wind speeds during the time when the pressure fell from 991 mb to the minimum (878 mb) and rose back to 1000 mb were used to calculate k. The value of k was found to be 11.2 +/- 2.0. A k value of 10.8 (20 for Um in km per hour) has been found to suit tropical Australian areas (Riedel & Byrne, 1989). The log of the wind speed was plotted against the probability for the pressure reduction associated with the same observed wind speed, and a considerable data scatter was observed (Figure 12).

DISCUSSION

Cyclone Recurrence

Records show (Pauga and Lefale, 1988) that there is a cyclone in Western Samoa resulting in significant damage to crops etc every 8 years or so, and that within a 30 year period, there is a cyclone that does considerable damage. Cyclone Ofa in February of this year was estimated by the author to be a 48 year event for Western Samoa 5 degree area and a 109 year event for a direct hit upon Apia. Fiji Meteorological Service reported it to have a maximum average wind speed of 100 knots with gusts to 140 knots near the center. Other calculations indicate the maximum wind speed may have been 93 knots. The 68 knot wind for 10 metres elevation at Apia produced by Cyclone Ofa would have a 24.3 year recurrence interval. Very severe cyclones are known to occur around 100 year intervals. However, the database upon which this study was made 40 years in duration, and estimates for return intervals should not be extended beyond 75 years or so. The estimate of 109 years given above may be in error by many years, and it should not be used for design purposes.

The shift in the recurrence curve for the winds observed at Apia to that for cyclone winds within the Western Samoa 5 degree square (Figure 4) is significant. For design purposes, the wind speed

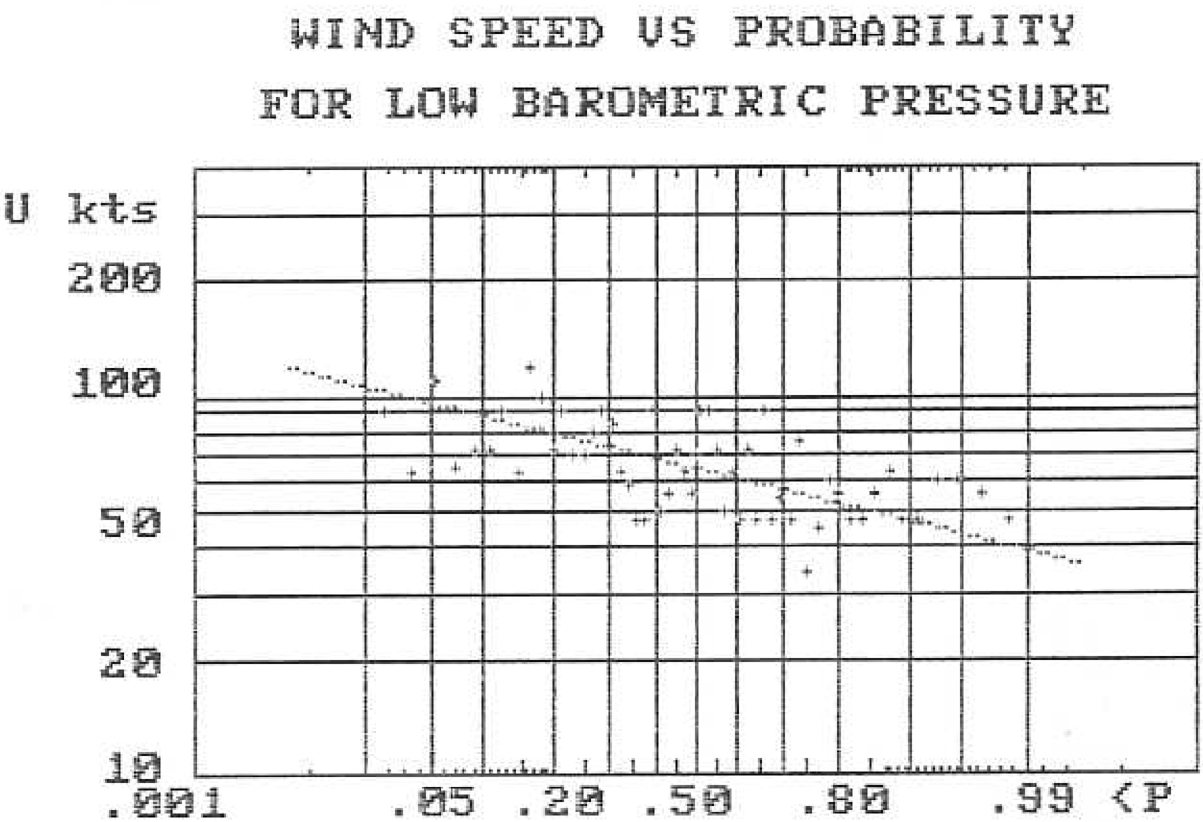

Figure 12. Wind speed associated with the probability for a given barometric pressure in 55 South Pacific cyclones 1906-1990.

selected for a given return interval should be equal to or greater than that given by the Western Samoa wind curve.

Waves Generated by Cyclone Winds

Waves generated within the cyclone have to be considered as they can continue outside of the generating field as swell and traverse great distances. However, waves generated within a cyclone passing within 200 nautical miles or so of Western Samoa may have significant decay before reaching Western Samoa, in particular if the waves feel the bottom. The significant wave height to reach Western Samoa may be only about 50 percent of that found in the generating field.

Once the recurrence interval for the maximum average wind speed is established, it is a simple matter to determine the recurrence interval for the deep-water significant wave height generated by the wind. These data are in Figures 6 and 7. If all of the parameters that characterize a cyclone are available, the maximum average wind speed and the wave height generated can be calculated. However, this is often not the case, and it becomes necessary to arrive at the significant wave height by some other means. The wind within a cyclone is curved toward the center, and as the cyclone progresses it can leave a generating field behind. A fully developed sea would not be expected to occur in a cyclone. One way to estimate the significant wave height is to assume a straight wind over a short fetch. In this case a fetch of 36 nautical miles was found to serve this need. The wave output from this study is given in Figure 5 and 7. The wind speed shown for Apia in Figure 2 is for the coast line. It would be about 10 percent higher out at sea. In Figure 5, a wind speed 10 percent higher than that at the coast line was used to calculate the significant wave height.

The maximum sustained wind speed recorded during the passing of Cyclone Ofa was 68.5 knots at 10 metres elevation. Figure 4 shows that this wind will have a 23.6 year return period. Figure 5 indicated a significant wave height of 22.7 feet or 6.9 metres. Figure 7 indicates a 25.2 foot or 7.7 metre significant wave height for a 30 year return period. The Waverider buoy located at Western Samoa showed a maximum wave height of 8 metres or 26.2 feet significant wave height at the time of the maximum sustained wind speed. The Waverider buoy is located some distance from shore, and as bottom friction will tend to reduce the offshore wave height as it approaches the reef, the value given by Figure 5 may better indicate the significant wave height near the reef.

Cyclone Forward Speed

Cyclone Ofa resulted in significant damage to Western Samoa partly because of its rather slow forward speed of 5.6 knots. The longer the winds and sea generated by the cyclone can act, the more damage results. Cyclone speed during the time of stronger winds was calculated for the 64 cyclones recorded in the Fiji reporting area between 1980 and 1990. These data are shown in Figure 8 and Figure 9. Very high and very low speed are less frequent then the median value of about 10 knots. There appears to be more slow cyclones of 0 to 5 knots than cyclone speeds greater than 18 knots.

Barometric Tide

The amount of storm surge, i.e. the increase in depth of water as the cyclone passes, is due to several components. Wave setup is one component that will be discussed in the application section of this report. The barometric tide contributes to the storm surge, and is caused by the reduced barometric pressure as the cyclone passes. Each millibar reduction in pressure is equivalent to about 10 mm increase in water depth. Figure 10 and Figure 11 present an analysis of the reported barometric pressures observed by ships and recording stations. They are rarely minimum pressures within the cyclone. The lowest pressure shown in Figure 10 was calculated from two observations made at known distance from the center of the storm. A line drawn through this point parallel with the line shown in the figure may be a good estimate for the minimum pressure.

During the passing of Cyclone Ofa the barometric pressure fell to 986 mb in Apia indicating a barometric tide of 0.19 metres. The astronomical tide, estimated to occur about 30 minutes early due to the increased water depth, was calculated to be 0.37 metres above mean sea level, and the wave setup was calculated to be 1.10 metres. These add to 1.66 metres above mean sea level. The depth of the storm tide was measure at the Apia Observatory during the event, and it was found to be 1.6 metres.

The return interval shown in Figure 11 may be satisfactory for estimation of the pressure on an island as it incorporates several variables into the value. These data may be more useful than knowing the minimum pressure in a cyclone as it relates to the barometric pressure that can be expected as a cyclone passes near an island. The median pressure reported was about 975 mb.

The wind speed and barometric pressure was reported for the cyclones analysed in Figure 10. A plot was made of that wind speed against the probability for the matching barometric pressure in order to see how reliable it might be for estimating the maximum wind speed from the reported barometric pressure. These data are shown in Figure 12. While the relationship exists there is a significant scatter to the data.

APPLICATION OF FINDINGS

Proposed Central Bank Building Site

The information developed in this study regarding the recurrence of extreme values for maximum wind speeds, storm surge, deep-water waves, and cyclone speed can be employed to select design values for the proposed building site shown in Figure 1. Certain assumption must always be made regarding the economic life of a structure. In Western Samoa an economic life of 75 years could be reasonable for a bank building.

Using the deep-water wave recurrence interval data shown in Figure 5, a wave of 29.8 feet is found for the 75 year return period. A wave refraction analysis for a 10 second deep-water wave arriving at the proposed site show that the wave energy would be spread over a distance of about 7.3 times the crest length in deep water. A model study reported by JICA (1987) show less than 40 and probably 30 percent of the wave energy for a 10 second wave could reach the site. The latter value is more conservative, and will be employed in this analysis.

The significant wave height to reach the shore at the proposed site would be 8.9 feet or 2.7 metres. The significant wave height of the waves to reach the harbour side of the filled land would be on the order of 20 feet for the 75 year return period; however, a longer return interval should be employed for this reach of seawall, say 100 years or so. If a cyclone having a return interval greater than 75 years should occur, some damage could occur to the breakwater. This would generally not be expected to be too serious, with damage to the breakwater probably limited to what could be repaired following the storm.

Assume that the design wave will break on the seawall at the site. It is a trunk section, not a point, so the stability coefficient, Kd, for 2 layers of smooth, rounded armor stone lay on a 1 to 2 slope, would be 2.1. Using the Hudson formula (US Corps of Engineers, 1977) the above design wave would indicate an armor rock of just under three tons (see Table I). It is very important that the filter layer and graded sized rock be used for this seawall, otherwise the waves will remove the fine fill material from behind the armor layers, and cause them to fail. No information regarding foundation conditions was considered in this analysis. Some bathymetry data ahead of the seawall would be required to determine whether the design wave would break before reaching the seawall.

TABLE I

SEAWALL DESIGN VALUES

Remarks: Breaking on trunk		Kd = 2.1
Wave H = 8.7	Wave P = 10	Wave L = 512
Wt Rock = 168	Slope 1: 2	N = 2

Material	Weight Rock Lbs	Diam. Ft	Thickness Ft	Remarks
ARMOR ROCK	5435	4.0	7.4	Smooth and rounded
W/10	543	1.8	1.8	Angular
W/200	27.2	0.7	1.0	Quary rock
W/4000	1.36	0.2	1.0	Mill run

Total Thickness = 11.2

Using other data developed in this study, an estimate of the storm surge can be made. The cyclone speed can be assumed to be 10 knots, the median value. Assume that the barometric pressure is 940 mb. This value is above the curve in Figure 11; however, the critical condition with respect to waves places the center of the cyclone southwest of Apia at a distance equal to the radius to the maximum wind speed. The barometric tide would be (1008-940)x0.01/.3048=2.23 feet, and the wave setup would be 2.7 feet (the wave setup is a complex function depending upon wave steepness, bottom slope, breaker depth and height, deep-water wave height, period, refraction etc. see Vol I page 3-93 of the Shore Protection Manual). Assume high tide of 1.37 feet above m.s.l. With a 10 knot storm there is a high probability that a high tide will occur during the cyclone passing. These components of water depth add to 6.3 feet (2 metres).

Other factors such as wave run up and overtopping can add a significant amount of water to the surface of the filled area. This can cause a temporary increase in the depth of water over the site. A temporary water level of 7.6 feet (2.3 metres) above m.s.l. can be expected. There is about a 35 percent chance that a larger cyclone will occur during the 75 year economic life of the structure. Some provision is indicated for this condition. Within the structure where water damage could occur, it would be prudent to allow for almost 10 feet (3 metres) above m.s.l. for location of power points etc.

The reader is cautioned not to compound safety factors in the above analysis, i.e. to always assume the worst condition, and add all of those conditions together. For example the minimum barometric pressure, maximum tide level, maximum wind speed from the most critical direction and maximum wave setup never all occur together. On occasion they may be close, but there are physical reasons that they do not happen at exactly the same time. Other factors must also be considered. For example bottom friction will generally reduce the maximum wave height some from the deep-water value, and refraction will reduce the wave further as it approaches the reef. In the above analysis the deep-water wave was estimated to lose 2 feet in height due to bottom friction, and the wave energy was estimated to spread over 20 percent greater shore line due to refraction before breaking at the reef. If these reductions in the wave were not considered the wave set up would be estimated at more then 4 feet.

Mulinu'u Point

A study was made regarding protection of this area (Carter, 1987). At that time the sand dredging operation had exposed the beach to severe wave attack. Nearshore dredging was stopped, and the sand has now returned to the nearshore area. It is assumed that the dredging will be controlled in the future as recommended in the 1987 study, so a new seawall design is now proposed for Mulinu'u Point that should result is a substantial saving of resources.

Information learned during Cyclone Ofa indicated that the criteria used to predict conditions at Mulinu'u Point were of sufficient accuracy to allow design of a safe seawall without over-design. Furthermore, as resources are limited in Western Samoa it is recommended that a 30 year design wave be employed for this site.

The 30 year significant deep-water wave height would be 24.2 feet or 7.4 metres (Figure 5). It would break at the reef and a secondary reef wave would form. The combined astronomical tide, barometric tide and wave setup would be on the order of 6.4 feet, so the largest wave to reach the seawall located at the west end of Mulinu'u Point without breaking would be about 3 feet in height. It is calculated to have a 9 second period and a wave length of 415 feet. Larger waves would break ahead of the seawall.

An armor stone of 223 lbs would be required where the 3 ft waves breaks on the seawall, and 195 lbs armor stone is needed elsewhere. Table II gives the details for the breaking condition.

TABLE II

SEAWALL DESIGN VALUES

Remarks: Non-breaking trunk — Kd = 2.4
Wave H = 3 — Wave P = 9 — Wave L = 415
Wt Rock = 168 — Slope 1: 2 — N = 2

Material	Weight Rock Lbs	Diam. Ft	Thickness Ft	Remarks
ARMOR ROCK	195	1.3	2.4	Smooth rounded
W/10	19	0.6	0.6	Angular
W/200	1.0	0.2	1.0	Quary rock
W/4000	0.05	0.1	1.0	Mill run

Total Thickness = 5.0

CONCLUSIONS

The conclusions reached in this study are based upon information developed herein. They are expected to be modified somewhat as more detailed recorded of cyclones are kept in the future, and a longer period of satellite records are available for analysis.

1. The probabilities and return intervals for given maximum wind speed and resulting significant wave height should be reliable for most coastal engineering works located in Western Samoa.

2. The occurrence of about six cyclone crossings every ten years in the 5 degree square of Western Samoa appears to have been relative constant since 1831 when records began.

3. During the very strong southern oscillation in 1982, there was a shift in cyclone activity. Vanuatu experienced some less and Tahiti had an increase. Western Samoa also had an increase in cyclone activity.

4. The shift in cyclone activity cited above does not warrant special consideration in the design of coastal works as the data upon which the study was based included this variation.

5. The estimation of the maximum wind speed made from the drop in barometric pressure appears to give a reasonable value at Western Samoa plus or minus 20 percent using a k value of 11.2.

6. The median speed for cyclones near Western Samoa appears to be 11 knots. Speeds of greater than 18 knots are not frequent. Most cyclones have speeds between 8 and 15 knots, although speeds of less than 8 knots are not infrequent.

7. The slower a cyclone moves, the greater are chances for it to include a high tide in its passing. The longer the large waves produced by the high winds attack the shoreline, the more damage will result.

8. The median barometric pressure reported for South Pacific cyclones is about 970 mb. This value may be 2 to 3 percent higher than the minimum pressure of the cyclone.

9. Where maximum storm surge is critical, the return interval based upon the reported barometric values given in Figure 11 would be appropriate.

10. To estimate of maximum wind speed in Western Samoa for wind stress on buildings, crop damage etc, the recurrence curve for Western Samoa, WS in Figure 4 is the appropriate curve. Specific sites may result in higher wind speeds due to local conditions.

11. To estimate the significant wave height of cyclone produced waves for Western Samoa use the curve in Figure 5.

12. The information developed in this study will be useful in the design of shore protection works in Western Samoa. In particular the smaller armor stone proposed for Mulinu'u Point should result in a significant savings of resources.

RECOMMENDATIONS

1. That the information regarding the recurrence interval up to 75 years for significant wave height given in this report be utilized in the design of coastal works to be located in Western Samoa.

2. That the recurrence interval up to 75 years for maximum sustained cyclonic winds given in this report be utilized in the design of engineering works being located in Western Samoa, with corrections for local conditions.

3. After twenty more years of cyclone data have been accumulated, that the values given in this report be updated to included those data, and extend the projected recurrence interval to about 100 years.

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1. The views expressed in this report are those of the Author and do not necessarily reflect those of the United Nations.

2. Mention of any firm or license process does not imply endorsement by the United Nations.

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