SECRET

Copy No. 5

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH
WELLINGTON, NEW ZEALAND

The FINAL REPORT *of* PROJECT "SEAL"

by

Professor T. D. J. LEECH
SCHOOL OF ENGINEERING
AUCKLAND UNIVERSITY COLLEGE
ARDMORE, NEW ZEALAND

18th December, 1950

R. E. OWEN, Government Printer, Wellington

SECRET

~~SECRET~~

COPY NO. 5....

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

WELLINGTON

NEW ZEALAND.

PROJECT "SEAL"

THE GENERATION OF WAVES BY MEANS OF EXPLOSIVES.

PROFESSOR T.D.J. LEECH

School of Engineering
AUCKLAND UNIVERSITY COLLEGE
ARDMORE,
NEW ZEALAND.

18th December, 1950.

IMPORTANT NOTE:

"Seal" Project is regarded as a joint United States/New Zealand project. Disclosure of the report or any information therein to a third country other than the United Kingdom is prohibited without the consent of the appropriate authorities in the United States of America and New Zealand.

~~SECRET~~

SUMMARY.

The project "SEAL" had its origin in a request of the Commander South Pacific Area (COMSOPAC) during April 1944, to the New Zealand Government for an investigation into the potentialities of offensive inundation by waves generated by means of explosives. During the period from February to April 1944 exploratory trials in New Caledonia indicated that there were reasonable prospects of developing techniques for favourable sites. The request incorporated two phases - the development of techniques, and the application of these to a trial upon an operational scale. Owing to changes in policy at a later date, the second part was cancelled.

The work was carried out by the 24th Army Troops Company, New Zealand Engineers with the co-operation of the Royal New Zealand Air Force, The U.S. Navy and the Royal New Zealand Navy between the 6th June, 1944, and the 8th January, 1945. Some 3,700 experiments were carried out with charges ranging from 0.06 lb. to 600 lb. in weight. T.N.T. was used generally, although C.E., nitro-starch and gelignite were used in some cases.

On the 25th July 1946, the second atom bomb trial took place at Bikini Atoll, under conditions permitting of direct comparisons with forecasts based upon the work of the "SEAL" Unit. These forecasts were verified within the limits of experimental error.

The investigations lead to the conclusion that offensive inundation is possible under favourable circumstances. Given low lying forshores and a shelving bottom off-shore, wave amplitudes of the order of those for recorded tidal waves, which have been disastrous, can be obtained. While T.N.T. or other explosives can be used, the engineering work specially involved introduces difficulties of considerable magnitude. The use of atomic bombs as multiple charges may be more practicable. The following matters of detail have been established:

(a) There is an improvement in the amount of energy transferred from the explosive to the water in the form of wave motion with increasing sizes of charges. (paragraph 11.7).

(b) The use of explosives at the upper critical depth adjacent to the water surface offers the advantages of higher performance and convenience as compared with deeply submerged charges (paragraph 6.2).

(c) The use of multiple charge arrangements imparts directional properties to the wave pattern, and produces markedly increased wave amplitudes along the axis of symmetry of the charge positions (paragraph 12.81).

(d) Single charges are impracticable (paragraph 15.3).

(e) Compared with recorded tidal waves, the wave lengths of the waves generated by explosives are smaller for given amplitudes.

(f) The ratio of the depth of water to the wave length at the charges is important, because for depths less than one-half the wave length, the energy efficiency falls rapidly with decrease in depth (paragraph 7.1).

(g) Hydraulic model studies are imperative before an assessment of the effects of inundation can be made, and for the determination of the best arrangement and position of charges (paragraph 15.6).

(h) For single charges, the empirical relationships have been confirmed by the observations made during the second Atomic Bomb trial at Bikini on the 25th July 1946 (paragraph 15.4).

Much work has yet to be done before all phases of the problem can be considered to be in a satisfactory position.

C O M M E N T .

Upon concluding this report, the Commander of Seal, No. 1 Unit, vacated his position as Professor of Engineering, Auckland University College, to become Chief Engineer, Scientific Services Branch, The Snowy Mountains Hydro Electric Authority, Australia.

All the experimental data is held by the Department of Scientific and Industrial Research, New Zealand, and any information concerning it or this report should be addressed to -

The Principal Secretary,
Defence Science Secretariat,
Department of Scientific and
Industrial Research,
Box 18, Government Buildings,
Wellington, C.1.,
NEW ZEALAND.

PREVIOUS "SEAL" REPORTS.

First Progress Report to Comsopac	23. 6. 44
Second " " " "	7. 7. 44
Third " " " "	21. 7. 44
Fourth " " " "	4. 8. 44
Fifth " " " "	18. 8. 44
Interin Report	31.10. 44

"SEAL" PROJECT.

INITIAL DISTRIBUTION LIST.

	Copy No.
The Chief of the General Staff, New Zealand	1
The Chief of the Naval Staff, New Zealand	2
The Chief of the Air Staff, New Zealand	3
N.Z. Joint Staff Mission, Washington, U.S.A.	4
N.Z. Joint Staff Mission, Washington, U.S.A., for transmission to appropriate United States Military Authorities	5) 6) 7)
N.Z. Scientific Liaison Officer, Washington, U.S.A.	8
N.Z. Scientific Adviser, London, U.K.	9
Chief Scientist, Ministry of Supply, United Kingdom, via New Zealand Scientific Adviser, London, U.K.	10
Director, Royal Naval Scientific Service-Admiralty, United Kingdom, via New Zealand Scientific Adviser, London, U.K.	11
Scientific Adviser to the Army Council, United Kingdom, via New Zealand Scientific Adviser, London, U.K.	12
Director of Scientific Research, Admiralty, United Kingdom, via New Zealand Scientific Adviser, London, U.K.	13
Scientific Adviser to Air Ministry, United Kingdom, via New Zealand Scientific Adviser, London, U.K.	14
Defence Documents Section, Department of Scientific and Industrial Research, New Zealand	15

TABLE OF CONTENTS.

Page

Introduction 1

SECTION I.

THE GENERATION OF WAVE SYSTEMS.

1.0 Introduction 6
2.0 Energy Considerations 7
3.0 Wave Generation by means of Falling Weights:
3.1 Introduction 8
3.2 Two Dimensional Studies 9
3.3 Three Dimensional Studies 12
4.0 Wave Generation by Means of Explosives:
4.1 Introduction 13
4.2 Qualitative Studies 14
4.3 Presentation of Experimental Observations
4.31 Linear Dimensions at Source 15
4.32 Linear Dimensions of Wave System 16
4.33 Correction of Observations to Deep Water Conditions 16
4.34 Correction of Observations for Float Inertia 16
4.35 Explosives 17
4.36 Dispersion 18
4.37 Energy Output of Explosive 20
4.4 Effect of Charge Position relative to Raft 21
4.5 Effect of Variations in Position of Raft relative to Water Level 22
4.61 Variation in Raft Thickness 25
4.62 Effect of Changes in Raft Size 27
4.63 Effect of Changes in Aspect Ratio 28
4.64 Properties of Raft Material 29
4.7 Miscellaneous Effects:
4.71 Effect of Changes in Raft Trim 30
4.72 Effect of Distributing Charge over Raft 30
4.73 Box Rafts 31
4.74 Barges 32
4.75 Influence of Sand beneath Charge in Barge 33
4.76 Effect of Covers on Barges 34
4.77 Plaster Barges 34
4.78 Directional Charges 35
4.79 Geometrically Similar Charges on Rafts 36
4.81 Investigation into "Scale Effect" 37
4.82 Depth Charges on Rafts 38
5.0 Generation of Waves by Surface Charges without Rafts:
5.1 Effect of Orientation of Rectangular Charges 39
5.2 Comparison of Priming Methods 40
5.3 Explosives other than T.N.T. 41
5.4 Charges fired adjacent to Water Level 41
6.0 Wave Generation by Submerged Charges:
6.1 Theoretical Notes 42
6.2 Submerged Charges-Effect of Depth of Charge 44
7.0 The Effect of Water Depth:
7.1 Introductory 47
7.2 Experimental Observations 48
8.0 Review of Work done Elsewhere:
8.1 United Kingdom 50
8.2 United States 52
8.3 Japan 53

SECTION II

THE PROPAGATION OF WAVE SYSTEMS.

Page

9.0 Introduction 55
10.0 The Law of Amplitude Decay:
10.1 Theoretical Considerations 55
10.2 Three Dimensional Systems, Surface Charges 56
10.3 Three Dimensional Systems, Submerged Charges 58
10.4 Multiple Charges 58
11.0 Characteristics of Wave Groups:
11.1 Theoretical Summary for Number of Waves in a Group 58
11.2 Number of Waves in a Group-Empirical Relationships 61
11.3 Interpretation of Records - Surface Charge 61
11.4 Interpretation of Records - Submerged Charge 63
11.5 Analysis of Wave Groups - Surface Charges on Rafts 64
11.6 Analysis of Wave Groups - Submerged Charges 68
11.7 Energy Efficiency 69
11.8 Scaling Laws 71
11.9 Wave Lengths 75
11.10 Wave Velocities 76
12.0 Multiple Charges:
12.1 Introduction 77
12.2 Significant Quantities 77
12.31 Linear Arrangements, Two Charges 78
12.32 Linear Arrangements, Three Charges 82
12.33 Linear Arrangements, Four Charges 84
12.34 Miscellaneous Linear Arrangements 86
12.35 Values of "n" for Linear Charges 88
12.36 Number of Waves in a Group 88
12.37 Wave Lengths 88
12.38 Discussion upon Linear Char es 89
12.41 Charges in the form of Vees, Three Charges 90
12.42 Charges in the form of Vees, Four Charges 92
12.43 Charges in the form of Vees, Five Charges 94
12.44 Values of "n" for Vee Arrangements 94
12.45 Number of Waves in a Group 96
12.46 Wave Lengths 96
12.47 Discussion upon Vee Arrangements 96
12.51 Charges in the form of Parabolas, Four Charges 96
12.52 Charges in the form of Parabolas, Five and Ten Charges 96
12.53 Number of Waves in a Group 99
12.54 Wave Lengths 99
12.55 Discussion upon Parabolic Arrangements 99
12.61 Charges Arranged On Circular Arcs 99
12.71 Form of Wave Pattern in Plan 101
12.81 Summary - Multiple Charges 102
12.82 Prediction of Wave Ampltidue 102
13.0 Some Anomalies:
13.1 Effect of Water Depth 103
13.2 The Induced Wave Train 103

Page

14.0 Behaviour of Waves Adjacent to Shore Lines:
14.1 Introduction and Observations on Tunami 104
14.21 Some Theoretical Considerations, Green's Law 104
14.22 The Effect of Depth 104
14.23 The Effect of Breadth 105
14.24 Wave Velocity 105
14.25 Velocity due to Gradual Rise in Water Level 105
14.26 Effect of Slope of Sea Bed 106
14.27 Change in Wave Height due to Oblique Propagation 107
14.31 Experimental Appoach, The Effect of Shoaling Water 107
14.32 Behaviour of Waves on a Shelf 108
14.33 Effect of Changes in Breadth 109
14.41 Miscellaneous Notes 109
14.42 Storm Waves 110

SECTION III

LARGE SCALE OPERATIONS.

15.1 Scope of the Section 111
15.2 Taronui Bay 111
15.3 Estimates of Performance in Deep Water for Large Single Charges 111
15.4 Estimates for the Second Bikini Atom Bomb Trial 112
15.5 Outline of Computations upon which Estimates were based 114
15.61 Model Criteria - Introduction 115
16.62 Wave Generation 115
15.63 Limits to Scale Factors 116
15.64 Lower Limit to Model Size 116
15.65 Further Significant Quantities 117
15.66 Behaviour above Normal Water Level 118
15.67 Characteristics of Non-Uniform Channel Flow 119
15.68 Summary 120

SECTION IV.

EXPERIMENTAL EQUIPMENT & METHODS.

16.1 Introduction 122
16.2 Field Experimental Station, Whangaparaoa 123
16.3 Experimental Pool 123
16.4 Float Type Wave Recording Equipment 124
16.5 Accelerometers for Recording Characteristics of Large Waves 125
16.51 Capacity Type Wave Recording Equipment 126
16.52 Principles of Method 127
16.61 Ultra High Frequency Radio Firing Equipment 130
16.62 General Scheme 130
16.63 Transmitter 130
16.64 Operation 131

	Page
16.65 Servicing	131
16.66 Rating	131
16.67 Receiver	132
16.68 Aligning	132
16.69 General	132
16.71 Remote Control Exploder	132
16.72 Operation	132
16.73 Description of Apparatus	133
16.74 Receiver	133
16.75 Test Procedure	133
16.76 General	134
17.1 Miscellaneous	134
18.1 Conclusions	134
18.2 Suggestions for Further Work	135
19.1 Acknowledgements	136
References	138

APPENDICES

I Gravity Waves Produced by Surface and Underwater Explosions, Dr. W.G. Penny.

II Notes on the Taylor-Penny Analysis, J.G. Millar.

<u>LIST OF PLATES.</u>

1. General View of glass walled tank with capacity type wave recording units in place.

2. Successive photographs of the initiation of a two-dimensional wave train by means of a falling weight.

3. Successive photographs of the initiation of an approximately two-dimensional wave train by means of a fire cracker.

4. Successive photographs of the initiation of a wave train by means of a 4.25 lb. T.N.T. A/T block fired with C.G. of block at Water level. (Series 147.1E).

5. Successive photographs of the initiation of a wave train by means of a 4.25 lb. T.N.T., A/T. block primed with powdered nitro-starch and No. 8 electric detonator, C.G. of block at water level. (Series 166.11C)

6. Successive photographs of the initiation of a wave train by means of a 4.25 lb. T.N.T. A/T block, primed with 2 oz. C.E., No.8 electric detonator fired with C.G. of block 5 ft. below water level in 13 ft. of water (Series 147.4E)

7. T.N.T. Charges used in "Seal" project.

8. Typical record given by float-type recorder for 4.25 lb. T.N.T. charge on raft, whose bottom was 3 in. below water level. (Series 147.16B).

9. Typical record given by float-type recorder for 4.25 lb. T.N.T. charge located 4 ft. below water level.

10A. 12/1 lb. nitrostarch charges in a line spaced at 12.4 ft. apart in water 14 ft. deep (Series 174.1).

10B. 10/1 lb. nitrostarch charges in the form of a parabola, $y^2 = 15x$, spaced 3.75 ft. apart in water 14 ft. deep (Series 169.1).

11. Taronui Bay.

12. Whangaparaoa Experimental Station.

13. Float type wave recording equipment.

14. Typical Accelerometer unit for recording vertical wave accelerations from which wave amplitudes, wave lengths and wave velocities can be obtained.

15. Capacity type wave recording equipment.

16. U.H.F. radio firing equipment.

17. Remote control exploder, A.T.D.B. Pattern.

18A. Model Barge for 1.38 lb. charges.

18B. Barge for 600 lb. charges.

PROJECT " SEAL "

INTRODUCTION.

1.1 ORIGIN OF PROJECT:

Project "Seal", or the investigation of the potentialities of inundation by means of artificially produce tidal* waves arose from a suggestion made by Wing Commander E.A. Gibson to Lieutenant General Sir Edward Puttick, Chief of General Staff (N.Z.) on the 13th January 1944. The former had noted, whilst engaged upon surveys in the Pacific Area during the period 1936 to 1942, that blasting operations upon submerged coral formations occasionally were attended by unexpectedly large waves. General Puttick instructed Colonel C.W. Salmon, the N.Z. Chiefs of Staff Representative in the South Pacific area (Enzedsopac) to place the proposal before Admiral W.F. Halsey, Commander of the South Pacific Area (Comsopac). Arrangements were made for Wing Commander Gibson, Professor J.M. Snodgrass, University of California, Division of War Research, who was then in the area investigating certain problems relating to submarine warfare, and Professor T.D.J. Leech, who was acting Director of Scientific Developments, New Zealand, to examine the idea at Noumea in February 1944.

2.1 NEW CALEDONIAN EXPERIMENTS:

It was decided to test the suggestion by ad hoc trials under the guidance of a team comprising Captain W.L. Erdman, U.S.N., Colonel Salmon, Wing Commander Gibson, Professors Snodgrass and Leech. Exploratory work was undertaken for the purpose of determining:

(a) The influence of certain variations in charge size and shape;

(b) The directional effects of a series of surface charges arranged to conform with certain geometrical patterns.

(c) Some idea of the mechanism of the action.

2.2 The results were incorporated in a report dated 31st March 1944, which was approved by Admiral Halsey and transmitted by him to the New Zealand Chiefs of Staff with a request that New Zealand undertake further investigations, as shown by the following extract:-

"The results of these experiments, in my opinion, show that inundation in amphibious warfare has definite and far reaching possibilities as an offensive weapon. It would be very desirable to have further developments carried out to establish a practicable method and procedure which could be used in offensive warfare. I would be grateful if this development could be continued to completion by New Zealand officers. All practicable assistance of facilities and personnel in this Command will be at your disposal."

---

*The word "Tidal" is not strictly correct. However, since the objective was the production of effects similar to those produced by naturally occurring tidal waves, the adjective has been used for the want of a better word.

2.3 Admiral Halsey's request was examined by the New Zealand Chiefs of Staff Committee, and proposals for implementation were submitted to and approved by the War Cabinet on the 5th May. They provided for the establishment of an Army Research Unit under the command of Professor Leech, who would be directly responsible to the Minister of the Armed Forces and War Co-ordination, Sir William Perry.

3.1 THE 24TH ARMY TROOPS COMPANY, N.Z.E.

The establishment of the Research Unit, known as the 24th Army Troops Company, N.Z.E., provided for the following Sections:

Headquarters Section (N.Z. Army)	64
Research Section (D.S.I.R.)	27
Works Section (R.N.Z.A.F.)	39
Photographic Section (R.N.Z.A.F. & D.S.I.R.)	 4
Explosives Section (U.S.N.)	10
Total	144

This unit was only partially manned.

The Headquarters Section was responsible for personnel, security and messing matters. The Research Section was under the direct control of the Commanding Officer. The Works Section was responsible for all constructive work. The Explosives Section was made up of specialist officers and petty officers of the U.S.N. Apart from the Headquarters Section, the others were responsible for meeting the technical requirements of the Research Section.

4.1 EXPERIMENTAL RESEARCH STATION:

The original suggestion for utilizing the fortress site on the Whangaparaoa Peninsula in the Hauraki Gulf, New Zealand was adopted. It was reasonably close to Auckland and the existing Army buildings had recently been reduced to a "care and maintenance" basis. From the viewpoint of security it was favourably situated. Close to the area, there were several sites suitably located for the larger experiments proposed. To cater for the small scale work, designed to determine the principles involved, an earthen dam was constructed in one of the valleys, which provided an experimental pool approximately 1,200 ft. long, 200 ft. wide and with depths varying in steps to 24 ft.

4.2 In addition to provision for basic development at Whangaparaoa, plans were laid for an operational test in New Zealand at Taronui Bay, North Auckland, between the Bay of Islands and Whangaroa, This was later abandoned.

4.3 The instrumentation associated with the Research Station called for considerable ad hoc development. Remotely recording wave mechanisms, radio controlled firing and manoeuvring devices had to be developed. These and many other details were brought to the prototype stage and operated satisfactorily.

4.4 It was originally intended that Leech would be assisted by a senior group comprising Professor Snodgrass and two eminent Australian hydraulic engineers, Messrs. T.A. Lang and F. de L. Venables. After protracted negotiations these gentlemen were not able to join the team, and the technical direction of the whole project remained throughout the responsibility of Leech.

5.1 SCOPE OF WORK AT WHANGAPARAOA:

Contemporaneously with the setting up of the Experimental Station, Dr. E. Marsden, Secretary, D.S.I.R. and Brigadier R.S. Park were able to discuss the question with U.K. scientists interested in cognate problems. These included Sir Geoffrey Taylor, Adviser to the Admiralty, Professor E.D. Ellis, together with Professor Chapman and Dr. W.G. Penny of the Imperial College of Science and Technology. These scientists had been interested in the study of the effects of firing submerged charges; and with the exception of Sir Geoffrey Taylor, all were pessimistic.

Somewhat later, Dr. Marsden discussed the problem with Dr. Vanevar Bush in Washington, and his views were more encouraging. Generally the points of view adopted were based upon theoretical analyses developed for single charges located at considerable depths. Subsequent experimental work demonstrated that the assumptions made in the development of the analyses were invalid for charges fired close to the surface.

5.2 The New Zealand approach to the problem was essentially experimental. While efforts were made to produce a satisfactory theory to explain the mechanism of wave generation with explosive charges close to the water surface, the mathematical difficulties proved intractable. However, the contributions by Sir Geoffrey Taylor and Dr. Penny were invaluable in the examination of a number of factors.

5.3 Detailed studies of the behaviour of single charges were made. The results demonstrated that single charges were inefficient in regard to wave production. However, a most significant factor was revealed, which accounted for the earlier observations (para 1.1) of occasional abnormally large waves. There is a small critical depth for the position of the centre of gravity of the charge below the water surface, at which the exchange of energy from the explosive to the wave train is a maximum. Small deviations from this critical depth, which is a function of the weight of the charge and the nature of the explosive, are accompanied by markedly rapid decreases in the resultant wave energy. This fact called for the precise location of charges in the later experiments. This shallow critical depth was unsuspected by the U.K. authorities, who had been thinking in terms of a critical depth of much greater magnitude. For a submerged charge, it had been shown by Penny that, when fired at this greater critical depth, the gas bubble attained its maximum size on breaking the surface and was able to produce the greatest wave amplitudes. These amplitudes were found to be less than those produced when the charges were located at the shallow critical depth discovered in the N.Z. experiments.

5.4 The use of multiple charges suitably located to conform with geometrical patterns was found to give superior results, not only as regards wave amplitudes, but in certain cases pronounced directional effects were produced. In all these cases the resultant wave amplitudes were sensitive to charge spacing, and charge location. The shape of the charge was also important.

6.1 SOME DIFFICULTIES:

Shortly after the "SEAL" Unit commenced operations on the 6th, June 1944, there was a change in the Command of the South Pacific Area. This, combined with the many suggestions by senior officers, resulted in changes of policy, without having due regard to the technical difficulties involved.

It did not appear to be realized that time is required to plan and implement experimental programmes. As a result much effort was wasted.

6.2 It was also unfortunate that the majority of the U.K. authorities were originally pessimistic. Subsequent events clearly demonstrated that, because of the absence of personal contact, they had based their decisions upon the effects of charges placed at the greater critical depth, and were at the time unfamiliar with the existence of the second and more pertinent critical depth near the surface. These factors, combined with the growing ascendency of the Allied Nations in the Pacific theatre, reduced the operational priority of the project and caused the New Zealand Government to close it down in January 1945, before the full experimental programme was completed and the fundamental scientific problems were solved.

7.1 SITUATION WHEN EXPERIMENTAL WORK CEASED:

The experimental station at Whangaparaoa was closed down on the 8th, January, 1945. At this time some 3,700 experiments had been carried out with charges ranging from 0.06 lb. to 600 lb. in weight. T.N.T. was used generally, although C.E., nitro-starch and gelignite were employed in some cases. The evidence resulted in the following conclusions:-

(a) Offensive inundation is possible under certain favourable conditions.

(b) Compared with recorded facts relating to tidal waves, amplitudes of the same order of magnitude can be produced, but their wave lengths are shorter.

(c) The efficiency of conversion from explosive energy to wave energy increases materially as the charge weight is increased.

(d) Explosives used close to the water surface produce superior results as compared with charges at greater depths. The location of the charge is critical. From practical considerations of manoeurvring this feature is advantageous.

(e) The use of single charges is not promising, but multiple charges suitably spaced and located with regard to geometrical considerations produce superior results.

(f) In 1944, the detonation of large masses of explosive presented a major unsolved problem. However, subsequent developments have shown that this need not be regarded as a ~~seiour~~ serious problem.

(g) With charges of T.N.T. of the order of 2,000 tons divided into, say, ten equal amounts and suitably disposed, wave amplitudes of the order of 30 to 40 ft. are within the bounds of possibility at distances approximating 5 miles off-shore, given favourable and commonly found sea-bottoms.

(h) The use of models similar to those used in Hydraulics Laboratories is imperative to determine the suitability of any given site and the best method of attack.

8.1 SUBSEQUENT EVENTS:

In 1946 Dr. Karl Compton, Chairman of the Atomic Energy Evaluation Board, visited New Zealand and discussed the Seal project with Leech, who had been invited to represent New Zealand and Australia in a technical capacity at the second Bikini atom bomb trial. The latter was unable to accept the invitation because of the critical conditions at the Auckland University College. However, he supplied data relative to the location of the charge at the critical depth nearer the water surfaacetogether with forecasts of wave amplitudes at predetermined points at which wave recorders were to be established. The records were, it was reported subsequently, in agreement with the forecasts within the limits of experimental error.

8.2 In February 1947, Leech was invited by the Assistant Secretary, U.S. Navy, to work with Dean M.P.O'Brien, Professor-in-charge of the Department of Engineering, University of California, upon the analysis of records obtained at Bikini. Again, the continuing critical conditions at the Auckland University College forced the Council to withhold its permission. During 1948, the University of California published a number of papers relating to certain phases of the project. Since 1948, several requests for the final report have been made by Dr. E. Marsden, N.Z. Scientific Liaison Officer, London, and the U.S. Embassy in New Zealand.

9.1 CURRENT WORK: During 1950 circumstances changed sufficiently to permit an effort being made to complete the report. At the same time a small group of post-graduate engineering students of Auckland University College became available and three of these have taken up small projects designed to fill gaps in the work done earlier. The projects are:-

(a) Studies upon certain anomalous effects when waves approach shoaling bottoms. (R.A. Marshall, B.Sc.)

(b) The review of and the development of methods designed to dissipate wave energy. (N.B. Carter.)

(c) A study in the augmentation of wave amplitudes by the application of surface impacts in series. (K.D.T. Shores).

At the end of the year theses will be submitted covering the work done under these headings.

10.1 SCOPE OF THE REPORT.

The accompanying report will summarize the principal facts which have emerged from the analysis of a considerable number of observations. The approach to the several issues has been primarily empirical. Dr. Penny's treatment for deep charges does furnish some significant results and for convenience it has been included as an appendix.

SECTION I.

THE GENERATION OF WAVE SYSTEMS.

1.0 INTRODUCTION:

1.1 Three methods of generating wave systems have been examined:-

(a) Waves produced by an impulse at the surface, which may take the form of mechanical impact by a solid or the expansion of a gas near the water surface.

(b) Waves produced by the expansion of the gas bubble resulting from the explosion of a submerged charge.

(c) Waves produced by the action of a relatively slow displacement under the water surface.

1.2 The first method is discussed in detail in this report. The impact of a solid body, or of the gas liberated by an explosion, with the water surface creates a cavity surrounded by an elevated fringe of water from which the wave system develops. Early work in New Caledonia with 600 lb. depth charges fired at depths varying from 150 to 600 ft. produced disappointing results, and these observations led to the detailed examination of this method. $\frac{\delta}{W^{1/3}} = 17.8$ to 71 $\frac{\delta}{W^{1/4}} = 30.3$ to 121.2

1.31 The second method has been considered theoretically by Penny (1) (Appendix II), and Kirkwood (2). Restricted experimental work (3, 4, 5, 6, 7) has been carried out in the United Kingdom and United States of America. Further experimental work upon this method of wave generation is discussed in this report and many hitherto obscure points have been in part clarified. The critical discussion of the New Zealand work in (7) was based upon rough exploratory experiments, and is therefore no longer applicable.

1.32 When a charge is fired at a considerable depth a gas bubble is formed which expands beyond an equilibrium condition (3, 8), and given sufficient depth it will contract again beyond a second equilibrium condition. For great depths it will expand again and the cycle will be repeated successively until the bubble breaks through the water surface. Just prior to breaking the surface (venting) a dome is formed and the water thus elevated brings about the initial development of the surface wave system. After venting a cavity is formed which upon collapse gives rise to the second phase of the wave system. At considerable distances from the source of the two phases, a wave group is formed. Theoretically (1) where the depth of the charge is just equal to the radius of the bubble produced, the wave amplitudes reach their maximum values. Experimentally the ratio of charge depth to maximum bubble radius accompanied by maximum wave amplitudes is approximately 0.65 (5). The charge depth for this condition has been termed the <u>critical depth</u>; but, because of the existence of another critical charge position nearer the surface, this will be known in what follows as the lower critical depth, as distinct from the second or <u>upper critical depth</u>. This second depth has not been mentioned in available references. The transfer of explosive energy to wave energy in the case of charges fired at the lower critical depth is less than in the case where similar charges are fired at the upper critical depth. L.K.

1.4 The third method has been examined in Japan (9,10), where it was believed that tunami (tidal waves created by seismic disturbances) have their origin in submerged rock displacements, such as slips. At the Earthquake Research Institute, Tokyo Imperial University, during 1933 small scale experiments were carried out in which waves were generated by the movement of a piston at the bottom of a shallow tank. These waves possessed characteristics similar to those often experienced during or just after earthquakes.

1.5 In the following discussion a number of basic ideas are presented with the view of rationalizing the analysis of the experimental results. During the early stages of the investigation attempts were made to extend the analytical studies of Cauchy and Poisson (11), to explain the exploratory observations without success. The theoretical treatments of Penny (1), Kirkwood (2) and Taylor (3) likewise fail to explain the behaviour resulting from charges located at the upper critical depth. Because of these limitations, and the necessity of obtaining data, which at the time could be rapidly used for operational planning, an empirical analysis of the problem was undertaken.

1.52 Scaling laws have been attempted (1, 2, 5, 7) upon the assumption that the efficiency of energy transfer from explosive to wave energy was constant. The evidence available shows this to be incorrect. Accordingly a different approach has been made wherein approximations based upon experimental observations have been adopted.

1.61. In order to gain some appreciation of the mechanism of wave generation by surface impact two series of experiments were carried out (13). The first series was conducted in a glass sided channel into which masses of rectangular form were dropped from varying heights. The second comprised observations of wave characteritics when masses were dropped into a pool. From these several important features productive of waves were noted.

1.62 Early thoughts upon possible methods of offensive inundation placed emphasis upon means for transporting and manoeuvring large quantities of explosive. In this way the association of charges with rafts developed, and much of the experimental work involved charges supported by rafts. Further, the use of multiple charges located according to definite geometrical patterns originated in the qualitative study of ripples produced by gangs of electric sparks in a tank.

2.0 ENERGY CONSIDERATIONS:

2.1 The energy per unit length of a single trochoidal wave of oscillation in deep water is given by (12):-

$$E_u = \frac{1}{2} w H^2 \lambda \left\{ 1 - 4.93 \frac{H^2}{\lambda^2} \right\} \qquad .....(1)$$

where w is the specific weight of the water.
H is the wave height from trough to crest.
λ is the wave length.

.0025
1-.0125
.9875

A summary of the available experimental results shows that the greatest useful values of H/λ vary from 0.048 to 0.054. Hence, for the wave systems considered in this investigation the following relationship for sinusoidal waves will give results accurate to within $1\frac{1}{2}$ percent. L.K.

PLATE 1.

General view of glass walled tank with capacity type wave recording units in place.

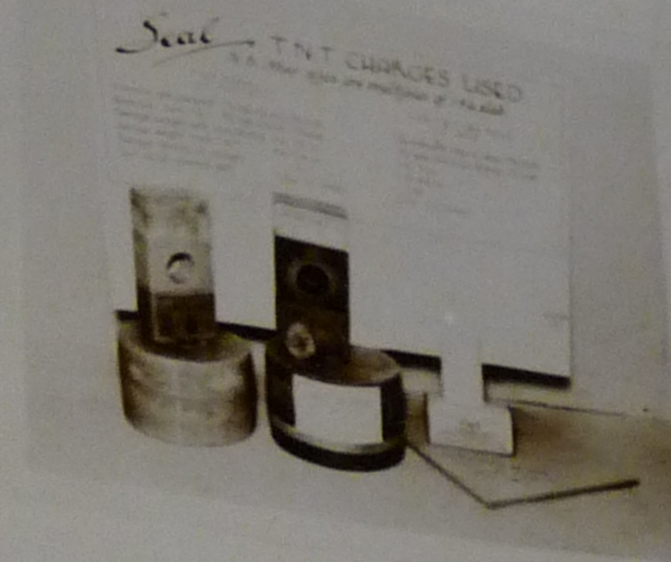


PLATE 7.

T.N.T. charges used in "SEAL" project.

PLATE 14.

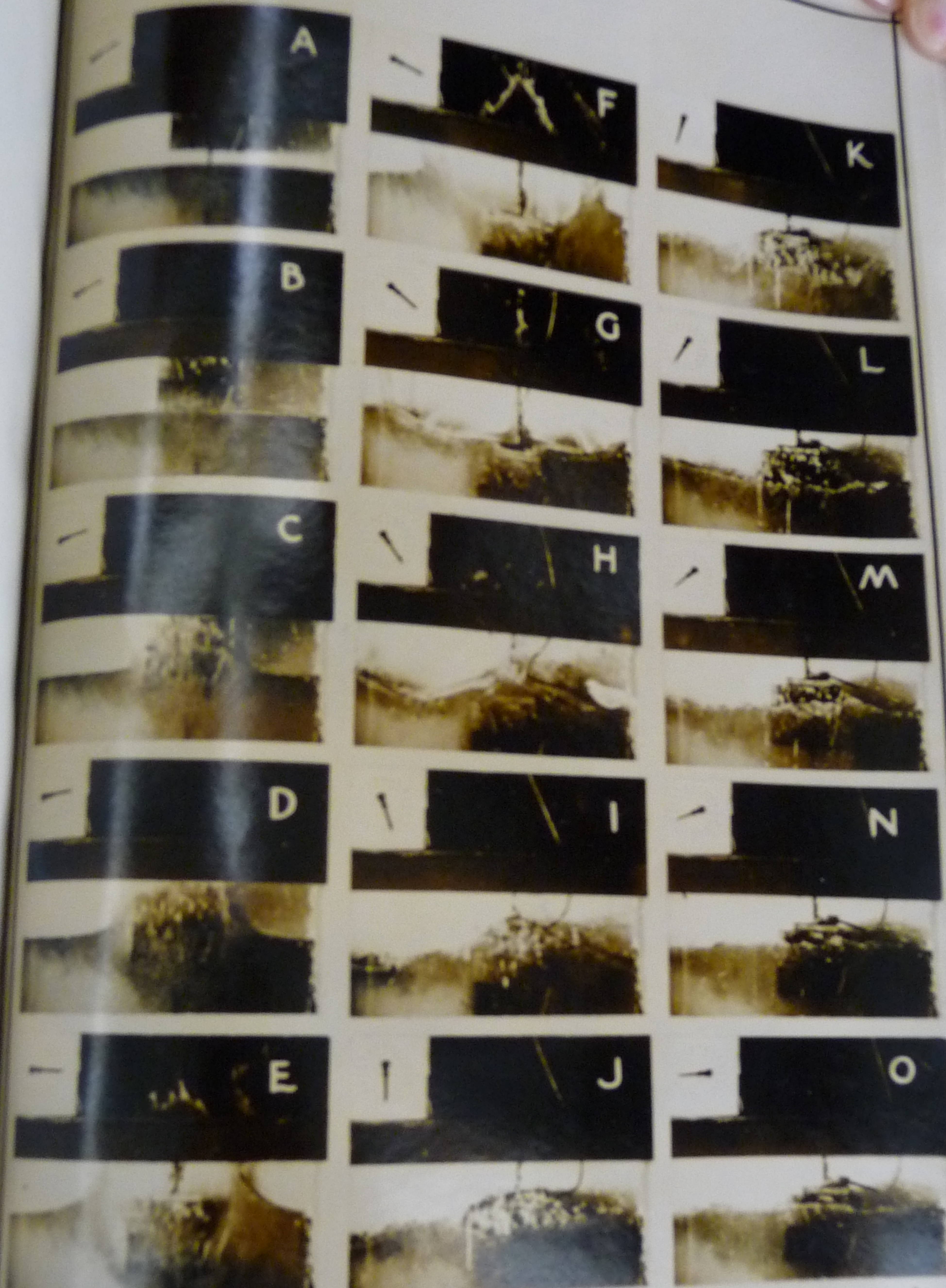
Typical Accelerometer unit for recording vertical wave accelerations from which wave amplitudes, wave lengths and wave velocities can be obtained.

PLATE 18 A.

Model barge for 1.38 lb. charges.

PLATE 18 B.

Barge for 600 lb charges.



Successive Photographs of the initiation of a two-dimensional wave train by means of a falling weight.

PLATE 2.

Successive Photographs of the initiation of an approximately two-dimensional wave train by means of a fire cracker.

PLATE 3.

PLATE 4.

Successive photographs of the initiation of a wave train by means of a 4·25 lb. T.N.T. A.T. block fired with C.G. of block at water level.

Photos by Victor 16 m.m. speed nominally 60 frames per second.

Series 147. I.E.

PLATE 5.

Successive photographs of the initiation of a wave train by means of a 4·25 lb. T.N.T. A/T. block, primed with powdered nitro-starch & No. 8 elec. det., C.G. of block at water level.

Photos by Bell & Howell 16 m.m. 2" lens - speed nominally 16 frames per second.

Series 166. 11 c.

PLATE 6.

Successive photographs of the initiation of a wave train by means of a 4.25 lb. T.N.T. A/T. block, primed with 2 ozs. C.E., No. 8 elec. det. fired with C.G. of block 5 ft below water level in 13 ft. of water.

Photos by Victor 16 m.m. speed nominally 60 frames per second.

Series 147. 4-E.

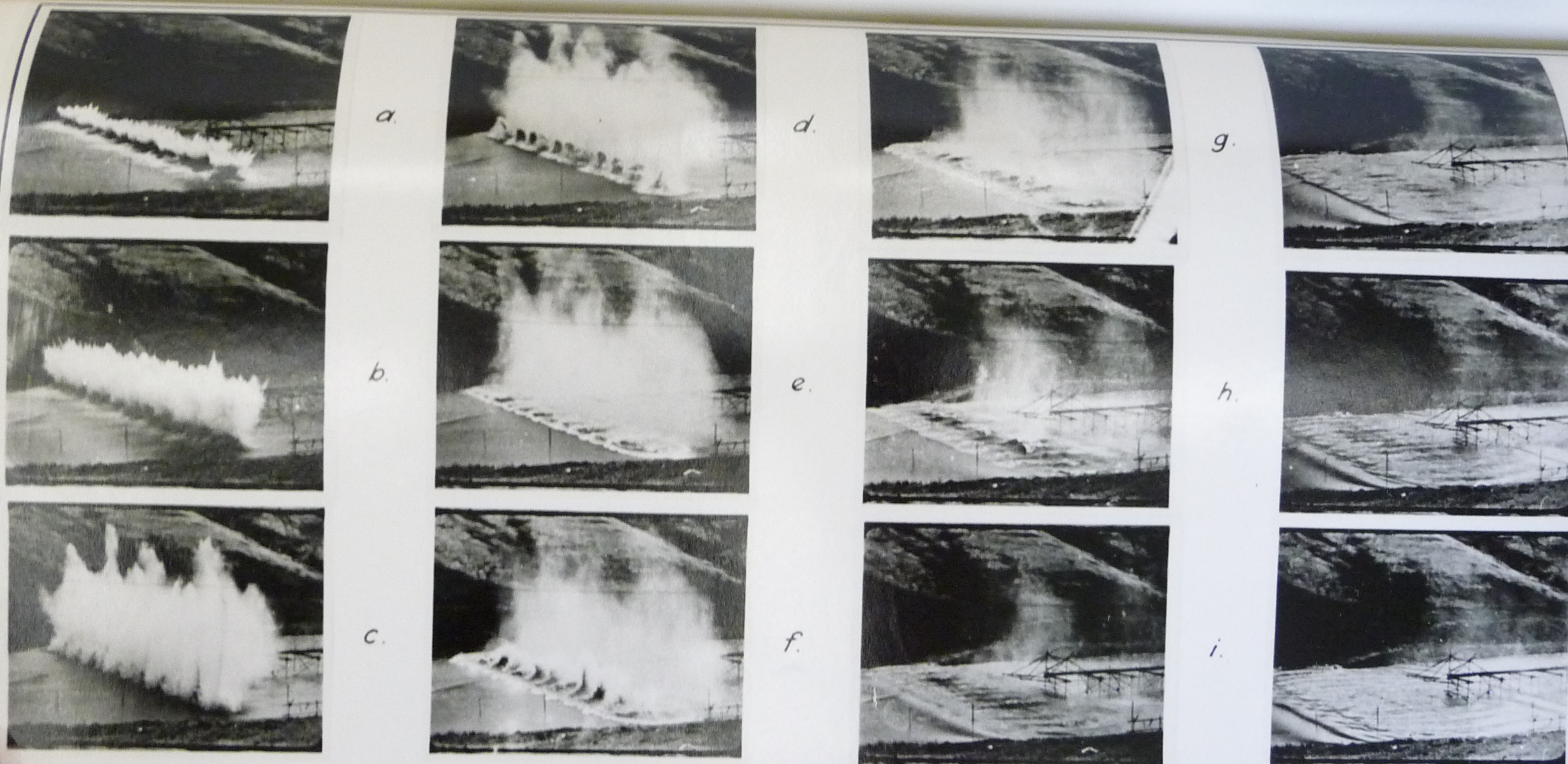


PLATE 10A.

12/1 lb. nitrostarch charges in a line spaced at 12·4 ft. apart in water 14 ft. deep (Series 174·1).

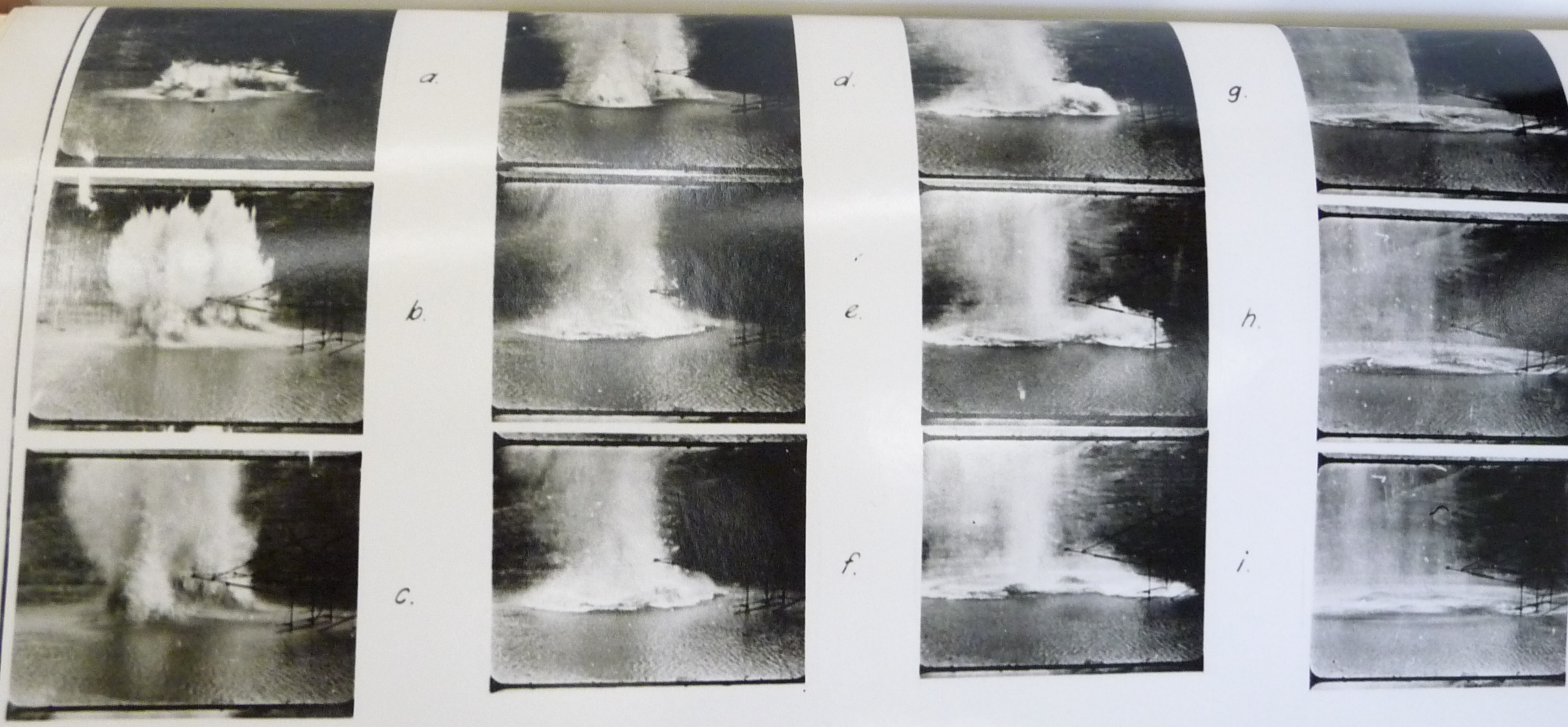
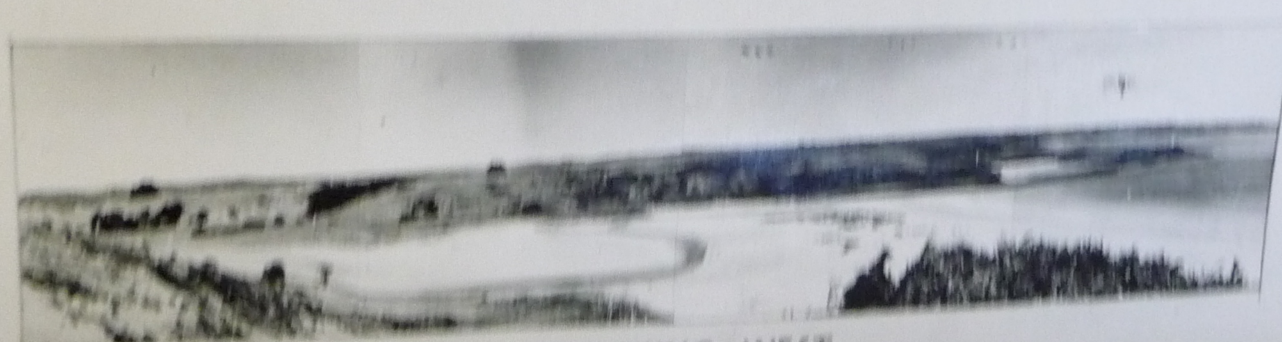


PLATE 10B.

10/1 lb. nitrostarch charges in the form of a parabola, $y^2 = 15x$, spaced 3·75 ft. apart in water 14 ft. deep (Series 169·1).

TAKOU BAY

LOOKING EAST



LOOKING WEST

PLATE II

(a). General view of Station and Pool.
A, Camp area; B, Pool; C, site for apron.

(b). Camp area showing administration and laboratory buildings and quarters.

(c). Near view of dam from right bank.
A, scour pipe and sluice valve.

(d). Near view of dam from the left bank.
Scaffolding commenced.

(e). Completed dam & pool filled to 12 ft..
A, recording hut; B, spillway.

(f). Near view of dam, spillway and facine wave apron.

(g). Preparation for concrete apron in foreground. Pool 12 ft. deep.

(h). A $4\frac{1}{4}$ lb. T.N.T. charge being fired at scaffolding.

PLATE 12.

Whangaparoa Experimental Station.

SECRET

cm

Copy No. 5

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH
WELLINGTON, NEW ZEALAND

The FINAL REPORT *of* PROJECT "SEAL"

by

Professor T. D. J. LEECH
SCHOOL OF ENGINEERING
AUCKLAND UNIVERSITY COLLEGE
ARDMORE, NEW ZEALAND

18th December, 1950

R. E. OWEN, Government Printer, Wellington

SECRET