Undersea Blasting for Honshu-Shikoku Bridge Route by Electromagnetic Firing Method

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A series of large scale undersea blasting operations has been completed at Kojima-Sakaide Bridge Route of Honshu-Shikoku Bridge Authority, which is one of the big civil engineering project in Japan. The technical difficulties faced in these blasting works were the depth of the sea, the rapid tidal current and the proximity of oil plant which meant ground vibration had to be minimised. In particular, the conditions at pier 6P necessitated employment of an electromagnetic firing method (E. F. M.). In this paper, the authors discuss the development of the E. F. M. employed, and the autual field procedure used. The results from field measurement were in good agreement with those expected on the basis of theoretical calculations. The undersea blasting operation was successfully completed without any problems.

1. Introduction

In Japan, we are now working on a big civil engieering project Honshu-Shikoku Bridge Route. Three routes have been proposed to connect the Honshu mainland to the Shikoku island, and the Kojima-Sakaide Bridge Route is the most important among them. This route crosses over the Bisan Straits (9.5 Km) from islet to islet by eleven bridges as shown in Fig.1.

Though undersea blasting work is necessary to get the sufficient bearing power on the bed rock to support the bridge structures, it is very difficult to perform ordinary blasting in deep seawater and rapid tide. In such cases, the electromagnetic firing method (E. F. M.) is very useful.

The authors concerned in extensive blasting work using the E. F. M. at the pier site of the South Bisan-Seto Bridge Route, the southernmost bridge on the Kojima-Sakaide Bridge Route. In this paper, the design of the undersea blasting work by E. F. M., the calculated results based on the electromagnetic theory, and the procedure of the field work are described as a historical case of actual remote-controlled firing.

2. Circumstances

The South Bisan-Seto Bridge is a suspension bridge, the largest on this route. The scale of this bridge is as follows: the span length is 1, 100m; the height of the main tower is 195m; the height of the bottom of the floor from the sea level is 65m; the diameter of the main wire rope is 118cm; the bridge is a double decker, the upper being a four-lane car road and the lower a four-lane train rail road.

The southern pier of this bridge, named 6P in Fig. 2, is located in the severe natural circumstances in that the maximum tidal current reaches 3.5 knots and the depth of the sea is 32m~34m. Alluvial and

Received on Feburary 15, 1983
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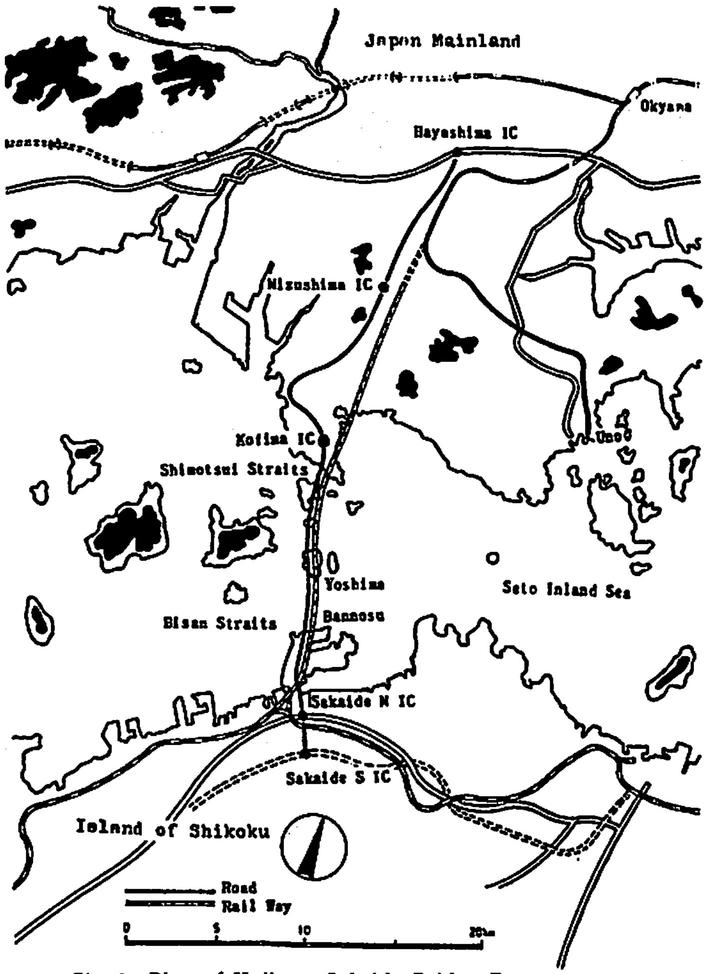

Fig. 1 Plan of Kojima—Sakaide Bridge Route

diluvial formations lie with a thickness of 10m～15m under the sea, and the granite bed rock is beneath them.

The pier 6P is formed by a caisson 38m (NS) × 61m (EW) × 55m (height). To set the caisson flat, and on the hard bed rock, the overburden and the eroded granite must be dredged out. It was planned that the bottom of the caisson would be faced in the plane of - 50m from the sea lebel and the blasting area would be 48m×69m, giving a surplus space of several meters around the caisson. Under the above circumstances, it was decided to apply the overburden blastibg method and the E. F. M. after theoretical considerations and preliminary experiments.

In this blasting work, a serious problem was that an oil refining plant holding many installations sensitive to ground vibration was located at a distance of 600～700m from the 6P site. To restrain the ground vivration at the above refining plant to less than 2 kines, the blasting area was divided into 21 lots, as shown in Fig. 3.

3. Designing of E. F. M.

3. 1 Strength of magnetic field

The blaster LB-4W consists of a pick-up coil, a firing condenser ($C=20\mu F^{*}$) and an electric switch. When this blaster is set in an alternating magnetic field, an electromagnetic force is induced between the terminals of the pick-up coil, and this force is rectified to D. C. and charged into the condenser.

The ability of LB-4W is 65V/AT/m and it takes about 90 seconds to reach full charge, though it is limited to 31V electrically in practice.

On the othtr hand, 2. 4mJ firing energy is required

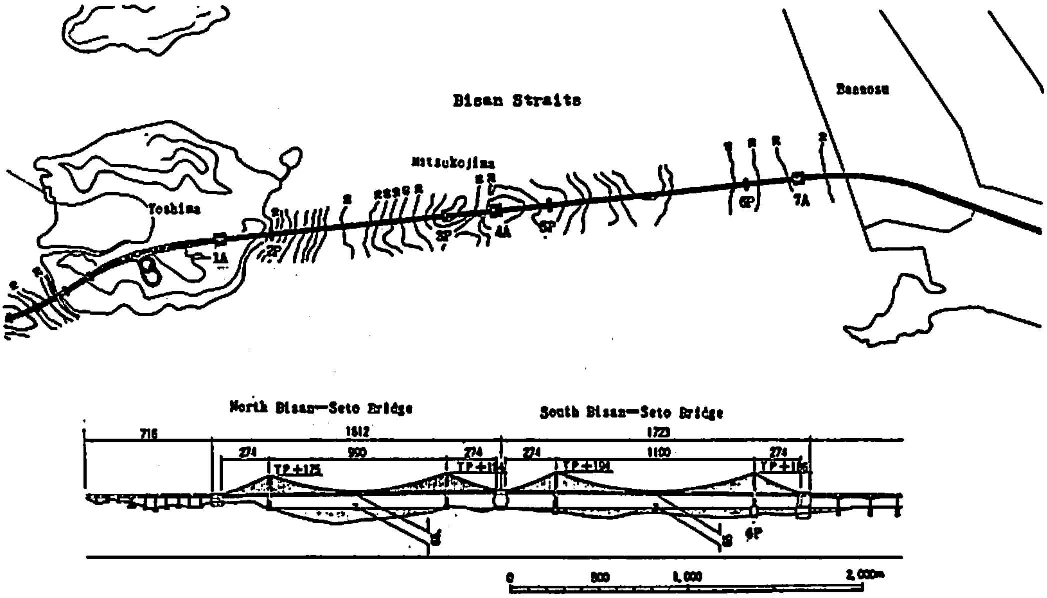

Fig. 2 Scales of South Bisan—Seto Bridge

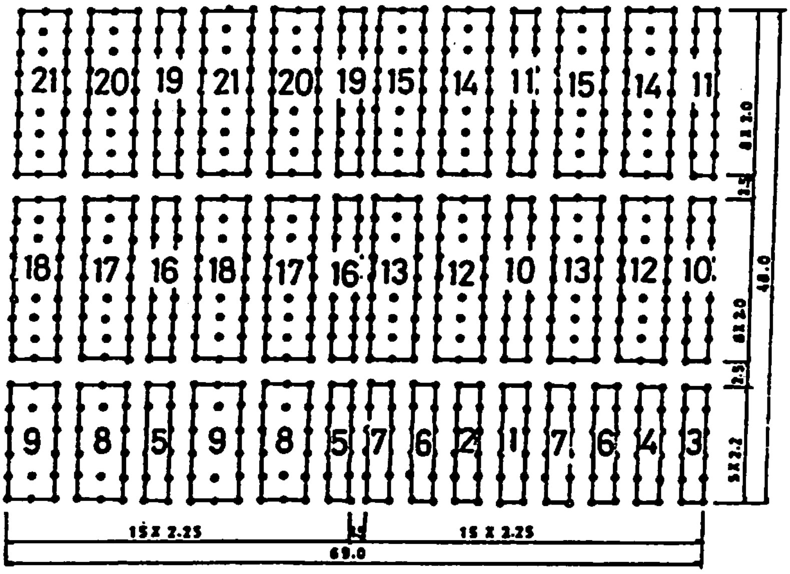

Fig. 3 Blasting pattern.

to detonate the cap EDX-2. From the relation of $Q=CV^2/2$, the voltage V charged in the condenser must be more than 15. 5V. Taking the safety factor of 2, the necessary voltage becomes over 31. 0V. Accordingly, the strength of the magnetic field acting on the blaster is given as 31/65=0. 478 AT/m.

3.2 Dimensions of exciting loops

When the self-elevating platform (SEP) works to drill the blasting holes at the corners of blasting area, the legs of the SEP off-set about 12m from the area. To prevent the loop cable being cut or damaged by legs of the SEP, and cover the whole blasting area by a loop, the exciting loop is required to be 80m×120m. But, considering the capacity of the electric source and the impedance of the loop, it seems somewhat difficult to keep the safety factor

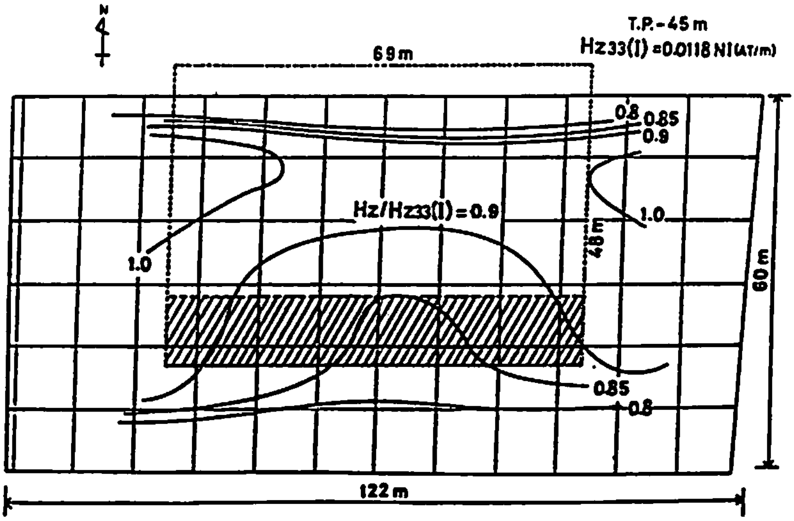

Fig. 4 Distribution of vertical magnetic field in plane of −45m (Loop (I))

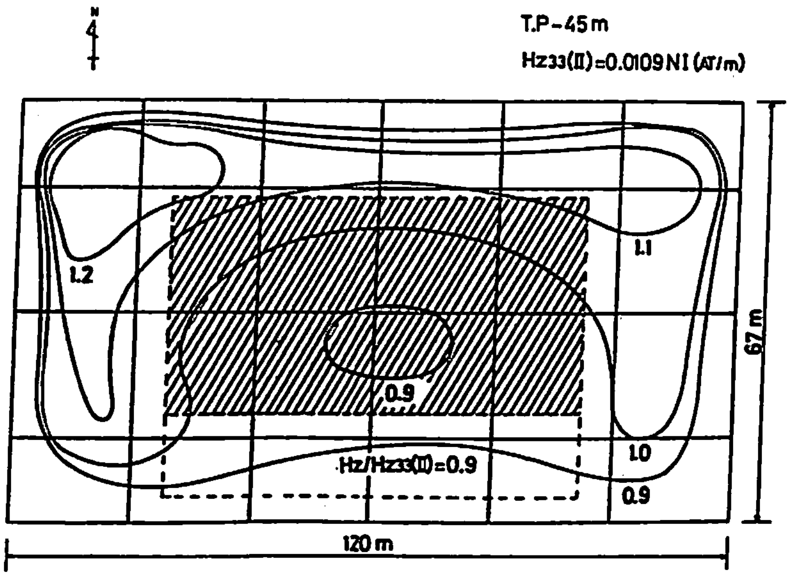

Fig. 5 Distribution of vertical magnetic field in plane of −45m (Loop (II))

of 2.

Therefore, the blasting area was divided into two parts, (I) is the south line block, (II) the center and the north line blocks together. For the former an exiting loop (I) of 60m × 120m was used, and for the latter a loop (II) of 67m × 120m.

3.3 Magnetic field by exciting loop (in air)

Exciting loop (I) was laid down on the sea bottom, which is slightly uneven and dips to the northwest. The actual shape of the loop is shown in Fig. 4. The depth of the loop center was −33m and the position of the blaster was about −45m. The magnetic field was calculated by use of a computer. Fig. 4 shows the distribution of the vertical magnetic field in the plane of −45m (H_z) which is expressed in the ratio to the field H_{z33}(I) at the center of the loop. H_{z33} (I) is calculated as

$$H_{z33}\ (I) = 0.0118\ NI\ (AT/m)$$

Where N is the number of turns of the exciting loop and I is the exciting current (A).

The least strength of H_z in the blasting area appears at the southside-center portion, where H_z= 0. 82 H_{z33}(I).

Similarly, Fig. 5 shows the distribution of H_z / H_{z33}(II) for loop (II) and the least strength appears near the center, where

H_z=0. 89 H_{z33} (II), and

H_{z33} (II)=0. 0109 NI (AT/m).

3. 4 Attenuation by seawater

When an electromagnetic field is induced in seawater, an attention should be paid to the attenuation of the field because the conductive current in the seawater can not be neglected, though it may be no account of the attenuation in air or on the ordinary earth. In case of the circular loop, the magnetic field occurring in a conductive medium has been explained in a previous paper.[1] In our situation, the conductive medium (seawater) is limited by the sea bottom, and the blaster is set in the bed rock, a non-conductive medium. In such a case, the solution is written as follows:

$$H_{2z}=\frac{aI}{2}\int_0^\infty \frac{2\lambda^2}{\lambda+\sqrt{\lambda^2-k_1^2}}e^z J_0(\rho\lambda)J_1(a\lambda),\ z\leq 0.$$ [1]

The solution for a rectangular loop has not been completed, but it has been confirmed experimentally that the distribution of the magnetic field by the circular and the rectangular loops almost coincide with each other near the center, provided that the vertical magnetic fields at the center of each loop are even. The radius a_1 of the circular loop corresponding with the vertical magnetic field H_{z33}(I) is given by a_1=42. 4m from the relation of H_{0c}=NI /2 a.[1] Similarly, a_2=45. 9m for H_{z33}(II).

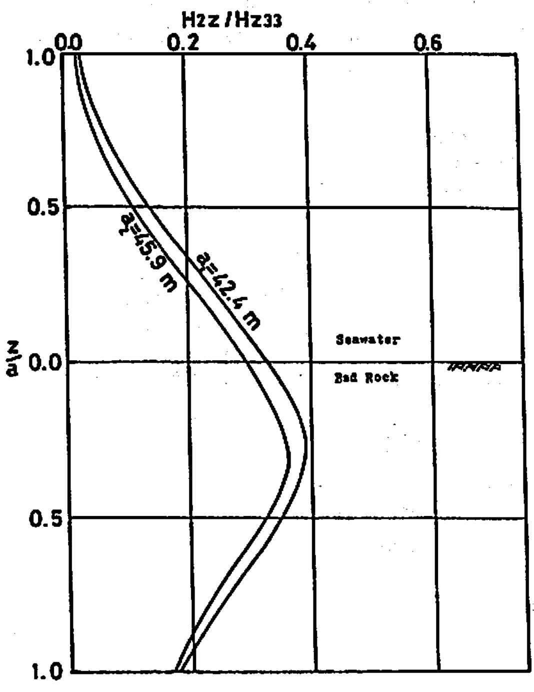

Fig. 6 Vertical magnetcfields along the axis of the exciting loops.

Fig. 6 shows the computed results of H_{2z} along the axis of the circular loop. In case of loop (I), z=12m, a_1=42. 4m, hence z/a =0. 283, then we obtain H_{2z} =0. 39 H_{z33} (I). In the same way, for loop (II), H_{2z} =0. 36 H_{z33} (II).

The highest degree of attenuation by the seawater appears at the center part of the loop, so that it is sufficient to make sure of the strength of the magnetic field at the center of the loop.

3. 5 Exciting cuorrent

From the above results, the induced vertical magnetic field with a minimum value H_{2z} at the center of loop (I) can be written as

H_{2z} =0. 39×0. 0118×NI×η

where, η is the charging ratio of the firing condenser, and it takes 90% for 60 seconds. Taking N=3, H_{2z} becomes H_{2z} =0. 0124 •I (AT/m).

It must be H_{2z} >0. 478 (AT/m), as above mentioned. We get finally, I_1 > 39. 8 (A).

Similarly, for loop (II),

H_{2z} =0. 36 × 0. 0109 × 3 • I × 0. 9 = 0. 0106 • I (AT/ m), and I_2>45. 1 (A).

4. Undersea blasting work

4. 1 Preparations

Some preparations were required before the blasting work. First, the working area was marked with bouys. Next, the exciting loop cable was laid on the sea bottom by a cable ship to make a rectangle of about 80m × 120m. Then, the cable was shifted and fixed to anchors by divers to make dimensions of 60m × 120m loop (I). (Later, this cable was shifted again to 67m × 120m loop (II)). A terminal of the transmitting cable was connected to the exciting loop by a waterproof connector and another terminal was led to the control room on the seashore, where the source of exciting current was set. Fig. 7 shows the sectional figures of both cables and Fig. 8 the schematic arrangement of equipment.

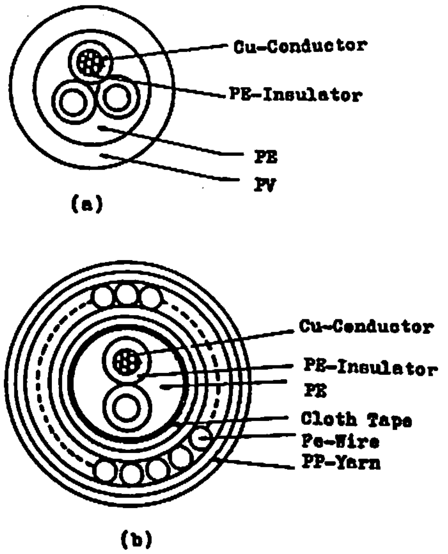

Fig. 7 (a) Section of the exciting loop cable
(b) Section of the transmitting cable.

The coincidence of the theoretical calculation with the actual output voltage was confirmed by field measurement. Fig. 9 shows the observed voltages along vertical bore hole below the center of loop (I). The voltages of the blaster at - 45m was 48. 3 under the exciting current of 57. 7 A and 550 hertz sufficient to detonate the cap EDX-2.

In addition, seismic detectors and pressure gauges to check ground vibration and water pressure were arranged at twelve points and three points.

4. 2 Drilling and charging

The diameter of each blasting hole was 146mm and the bottom of the hole was located at − 45m. The blasting holes were drilled by 6 "Wellman" boring machines which were equipped on the SEP, and the holes were protected by hard vinyl pipes.

The dynamite for undersea blasting GX-1 was composed of 50～70% NG-gel, 15～20% ammonium nitrate, 10～20% barium sulphate, and other materials. It was packed in units of 2 Kg, and the diameter was 76mm and the length 335mm. At the patterns of No. 1, 4, 6, 7, the charges were 30Kg/hole and the rest were 20Kg/hole. The primer dynamite consisted of the blaster, the cap EDX-2, 25g tetryl as the booster and the 2Kg GX-1 and was at the top of each charge. The primer dynamite and the charges were put together as a cartridge in vinyl pipe, and lowered into the blasting hole as soon as it has been drilled.

4. 3 Blasting

After the completion of charging, the SEP was evacuated from the working area to a distance of hundreds meters. The blasting was executed in time of the pause of navigation. When the chosen time had come, the electric source in the control

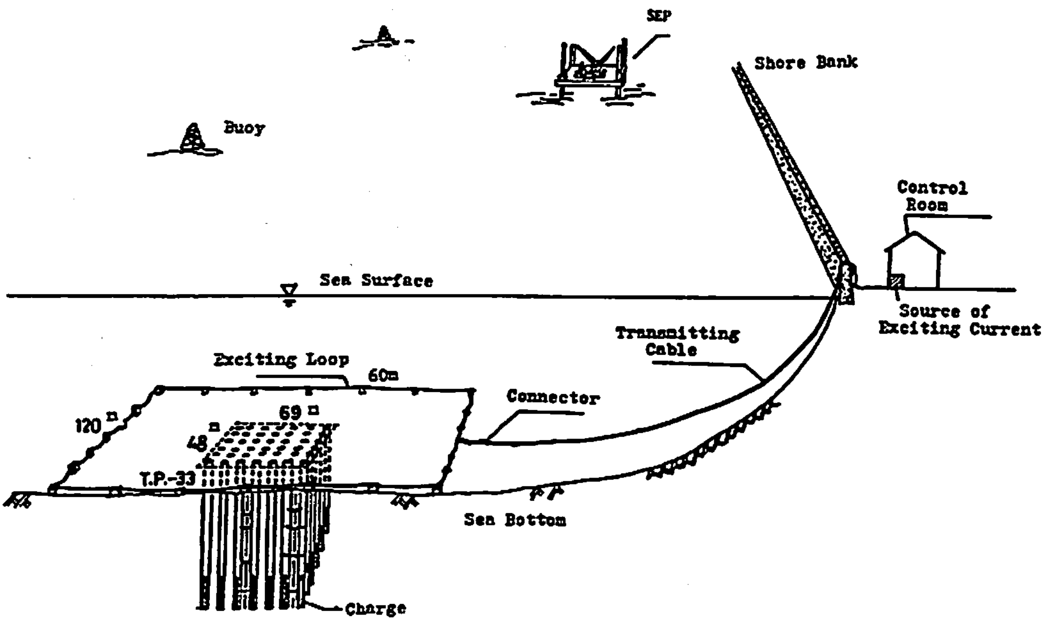

Fig. 8 Schematic arrangement of equipment

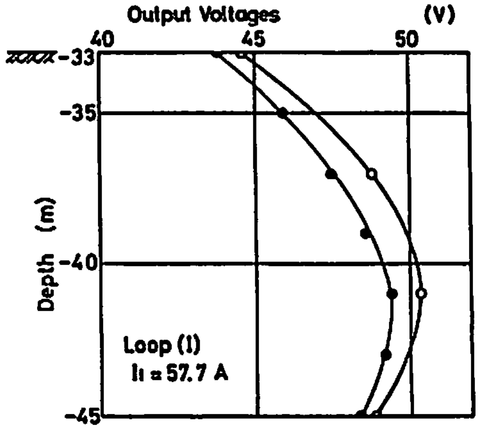

Fig. 9 Output voltages of the blaster in the bore hole at the center of loop I.
—○— Calculated
—●— Measured

Table 1 Data of blastings.

No.	Date	Number of holes	Charges (kg)	Max. kines at S4
1	Nov. 12. 1980	12	360	1. 54
2	Nov. 20. 1980	12	360	0. 98
3	Nov. 30. 1980	12	360	0. 97
4	Dec. 9. 1980	12	360	0. 69
5	Dec. 18. 1980	24	480	0. 77
6	Dec. 27. 1980	24	720	0. 98
7	Jan. 12. 1981	24	720	0. 92
8	Jan. 22. 1981	36	720	0. 91
9	Jan. 30. 1981	36	720	0. 84
10	Feb. 14. 1981	36	720	0. 98
11	Feb. 22. 1981	36	720	1. 11
12	Mar. 4. 1981	54	1080	1. 57
13	Mar. 13. 1981	54	1080	1. 27
14	Mar. 23. 1981	54	1080	1. 43
15	Apr. 1. 1981	54	1080	1. 59
16	Apr. 12. 1981	36	720	1. 19
17	Apr. 21. 1981	54	1080	1. 58
18	Apr. 30. 1981	54	1080	1. 38
19	May. 9. 1981	36	720	1. 50
20	May. 17. 1981	54	1080	1. 79
21	May. 26. 1981	54	1080	1. 35

room was switched on and the exciting current of 5500 hertz flowed to the loop by 56A-57A under the usual conditions. After 60 seconds, the switch was opened and all charges fired at once. According to the experimental results, the irregularity of firing time was less than 1 ms.

After the completion of each blasting, the resistance of the cables, insulation resistance between the cables and the seawater, and the output voltages of the blaster at the center of the loop (sea bottom) were checked.

Total twenty one blastings were carried out in this way in the order shown in Fig. 3. Table 1 shows the data of those blastings. The work was completed satisfactorily in about a half-year without any troubles accidents.

5. Conclusions

When the electromagnetic firing method is used in the sea, the attenuation of the magnetic field caused by the seawater is very important. In fact, the effect of the seawater to the magnetic field was related mearly to the square of the radius of the exciting loop, and the intensity of magnetic field, i. e. output of the blaster, dropped to 36—39% of that in air, as the exciting loop was considerable large in this field.

It has been established to forecast the distributon of the magnetic field by the theoretical calculations, and the both results of calculations and the field measurements were in good accord, so we could accomplish this work with confidence. and all blastings were completed succesfully.

Acknowledgements

This work was carried out with the help of the Sakaide Office of Honshu-Shikoku Bridge Authority and T. O. M. T. Joint Venture. The authors thankful to the above organizations and to the Research Institute for Safety Engineering for support of this investigation.

Specially we wish to express our hearty gratitude to Mr. Sugita, Manager of the Sakaide Office of Honshu-Shikoku Bridge Authority.

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電磁誘導起爆法による本四橋水中発破工事

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日本の最大土木工事の一つである，本州四国連絡橋工事の児島一坂出ルートの水中発破工事が終った。この水中発破工事では技術上の難問として，水中発破施工場所の水深が深いこと，潮流が速いこと，発破現場のすぐ近くに石油精製工場があり，発破の振動を最小限にすることがとりあげられた。

特に6P地点では電磁誘導法による水中発破を採用する外はないということとなった。電磁誘導発破法を開発してこれを実際の工事に用いた結果を記述し，理論計算と施工上の諸問題とが期待通りであり，しかも水中発破は無事成功をおさめたことを報告する。