hard steel plates, is locked down, at the terminus, to a strong iron-plate fixed in the Guard's carriage. The key of this lock, and also the key by which access can alone be obtained to the interior of the chest, is kept at the principal terminus, by the officer who has charge of the cash.

Each Station-master is provided with a key, which opens a small lid at the top.

When he has money, or small valuable parcels to send, he unlocks the small lid, places the bag of money, or the parcel, in an open drum underneath (Fig. 2), moves a handle which turns the drum, and the cash is dropped inside (Fig. 3). He must then move the drum back to its place and see that the money has fallen into the chest, before he can shut the lid and take out the key. Thus it becomes impossible for him to leave the lid unlocked.

When the chest arrives at the terminus, it is unlocked from the frame, taken into the office and placed on a similar frame, to which it is locked down. The cash-keeper only, can with his key, obtain access to the money, and unless great violence be used, the chest cannot be removed from its position.

This kind of chest has already been found very useful, in the prevention of robberies, and in insuring the punctual transmission of cash from the various stations on several railways.

March 14, 1848.

JOSHUA FIELD, President, in the Chair.

No. 782. "Account of the Effect of the Storm of the 6th of December, 1847, on four Sea Walls, or Bulwarks, of different forms, on the coast near Edinburgh; as illustrating the principles of the construction of Sea Defences."* By William John Macquorn Rankine, Assoc. Inst. C. E.

There are few branches of engineering with respect to which greater uncertainty and difference of opinion exist, than that of the construction of sea walls and breakwaters.

The question has been frequently before the Institution, and in its archives there is much useful information on the subject.

The valuable paper of Lieutenant-Colonel H. D. Jones, read in 1842,† may be particularly referred to, as its conclusions are to a

* The discussion on this paper was extended over portions of three evenings; but an abstract of the whole is given consecutively.

† *Vide* Minutes of Proceedings, 1842, vol. ii., p. 124.

certain extent verified, by the facts which have come under the author's observation.

Conceiving that every addition, however small, to the facts recorded respecting the efficiency of such works, must tend to bring the principles of their construction nearer to certainty, the author felt it to be his duty to lay before the Institution, transverse sections (Plate 8) of four sea walls, upon a portion of the coast of the Frith of Forth, near Edinburgh, having an exposure towards the north and north-east, and to give an account of the effect upon them, of one of the most violent storms on record in this climate, which took place on the 6th of December, 1847.

Figs. 1 and 2, Plate 8, represent the sea wall of the Leith branch of the Edinburgh and Dalkeith railway, which was completed in the winter of 1837. Fig. 1 is the transverse section, as originally designed by the consulting engineer, Mr. Walker. Fig. 2 is the transverse section, as the wall was actually built.

The author was resident engineer of the railway whilst this wall was executed, and it is the only one of the four walls, the formation of which he can describe from actual inspection, during the progress of the work; the other three sections are, therefore, to be regarded rather as giving the external form, and the general style of building of the walls they refer to, than as affording minutely accurate information respecting the details of their construction.

The deviations from the original design and specification were chiefly in matters of detail, and will be apparent on an examination of the two sections. The most important were the following:—

The hearting was composed of concrete, instead of rubble.

The parapet was omitted, as no bulwark of ordinary height could have kept off the spray, which sometimes rises 20 feet above the wall.

A small wall was added at the landward side of the embankment, so as to retain the sand in a sort of trough; for, until this was done, it was found that the spray, collecting in pools on the surface of the embankment, after a gale, washed away the material in large quantities; but after the formation of the trough, the water subsided by filtration through the sand, without doing any damage.

As boulder stones were abundant on a neighbouring part of the beach, they were used to form a nearly horizontal pitching to secure the foundation against being undermined, instead of using the sheet piling shown in the section, Fig. 1.

It was found, from the effects of a violent gale which took place during the progress of the work, that the coping stones, which weighed about half a ton each, were liable to be lifted by the sea,

thus exposing to destruction the courses of smaller stones beneath them. They were therefore connected together by cylindrical cast iron dowels, $1\frac{1}{2}$ inch in diameter, and 12 inches long, placed in the line of the centre of gravity of the stones, and penetrating 6 inches deep into holes made to fit them, in each stone. This mode of connexion has answered its purpose perfectly, not a single coping stone having been lifted by the most violent storms.

With the exception of the alterations and additions just mentioned, the wall was executed almost exactly according to the original design of the consulting engineer.

The total length of the wall is about 750 yards, and its height is $13\frac{1}{2}$ feet above the beach, at the most exposed part, diminishing to about 6 feet at the ends; this gives only 4 feet above the level of high water of equinoctial spring tides. The least thickness is 5 feet, the greatest thickness is 10 feet: the back of the wall is vertical; the face has a batter of about 5 inches in a foot, at the lower part, and towards the upper part it becomes curved, and overhangs slightly at the top.

The whole of the masonry is of white sandstone from Craigeleith quarry. The foundation course is composed of large flat stones, 12 inches thick, laid horizontally, at an average depth of 4 feet below the surface of the beach. The stratum on which it rests is clean sea sand, with a slight mixture of fine gravel; firm when the tide is low, but when saturated with water, it is so moveable that the author has found stakes, which had been driven 2 feet deep into the beach to mark the line, shifted during a stormy night 3 feet from their former place, without losing their vertical position, or rising out of the sand; yet the foundation of the wall has never shown the slightest symptom of insecurity. This is one amongst many instances of the safety of a foundation on pure sand when it has no outlet to escape laterally.

The face of the wall was built in courses, from 6 inches to 12 inches in thickness, of squared hammer-dressed stones, averaging 2 feet in depth; the back was built of coursed rubble, averaging about 18 inches in depth, and the interior was filled with concrete, composed of gravel from the beach, laid in courses 12 inches in thickness, as the masonry was finished. There are two courses of bond stones as shown in the section. The coping stones are 14 inches thick, and average 3 feet in length.

At first, the joints of the face were protected, by scraping out the mortar for a depth of 2 inches, and pointing them with cement; but as it was found, that the sea sometimes broke off and extracted large pieces of the cement, even after it had set, it was considered advis-

able to lay the remainder of the face stones in cement, for a depth of 4 inches inwards, whilst building the wall.

In order to promote the accumulation of sand and gravel at the base of the wall, several timber groynes, formed of planks set on edge between a double row of piles, were placed at right angles to it.

The whole of the masonry was constructed by workmen in the employment of the Company, under the immediate direction of Mr. Somerville, upon whom the style of execution reflects great credit.

The gross average cost of the wall was somewhat below twelve shillings per cubic yard.

Almost immediately after the completion of this work, the most violent north-east gale occurred which had been known on that part of the coast for twenty years; but the wall, though exposed to the full force of the waves, did not sustain the slightest damage.

Ten years afterwards, on the 6th of December, 1847, a more violent storm occurred, which damaged, or partially destroyed almost every other sea defence on the neighbouring coast; yet the sea wall of the Leith Branch Railway escaped without injury.

The horizontal pitching at the foot of the wall was alone damaged to a slight extent, by some of the stones being lifted out of their places by the waves; but they were generally deposited near their original sites, so that the necessary repairs could be made at a trifling cost.

The sections (Figs. 3, 4, and 5) represent sea defences between Newhaven and Granton, the foundations of which rest chiefly on shale, or on sandstone, which strata crop out on that part of the coast.

Fig. 3 represents the cross section of a much older sea wall and bulwark, on the turnpike road between Newhaven and Trinity.

As the wall was not breached at any point by the storm of the 6th December, the author is not able to give its thickness, nor the depth of its foundation. The face is nearly perpendicular, and it is built entirely of rubble, laid in mortar, with a pointing of cement in the joints of the lower courses. The roadway is about 8 feet above high water of spring tides, and the parapet rises 4 feet 6 inches higher.

The foundation of this wall is protected by a dry stone pitching, sloping at angles of from 30° to 40° .

The only effect of the storm was, that the upper part of the pitching, at several points, was carried away, to the extent shown

in the section. The vertical wall was not damaged, except at one point, where a fishing-boat being thrown upon the road by the waves, overturned an iron railing, which at that spot filled a small opening in the parapet.

Fig. 4 is a section of the sea wall of a portion of the Edinburgh, Leith, and Granton Railway.

This wall is 2 feet 6 inches thick ; its section approaches to the form of a hyperbola. For a depth of about 7 feet below the base of the parapet, it is nearly perpendicular, and has counterforts of the form shown in the section. Below the point marked **A**, it becomes a dry stone bulwark.

The effect of the storm of the 6th December upon this structure, was to form two long breaches, by which the building was entirely demolished, with the exception of the lower portion of the dry stone bulwark (marked by a darker colour in the section), and several of the counterforts, which were left standing alone.

This result was obviously occasioned by undermining ; the stones between the point **A** and the bottom of the breach being extracted by the waves, the upper part of the wall, having no independent foundation, fell into the sea.

Fig. 5 represents the sea wall of the Edinburgh, Leith, and Granton Railway, at and near Granton.

This is a sloping bulwark of a nearly parabolic form. It is built dry, except the string course and parapet, and consists of stones, which are, as the section shows, much larger and heavier than those employed in building any of the walls previously mentioned, most of those in the lower part of the slope weighing full half a ton each.

The stones of the heavy string course, on which the parapet rests, are connected by means of a flat malleable iron bar, measuring $2\frac{1}{2}$ inches by $\frac{3}{8}$ inch, laid along their upper surfaces, and attached to the stones by iron spikes $\frac{5}{8}$ inch in diameter.

The coping stones are connected with each other, and with the dado of the parapet, by T shaped iron cramps.

The damage done to this wall, by the storm, was comparatively trifling ; it consisted in the overturn of a few yards of the parapet and string-course, and of the dry building immediately beneath ; the iron connecting bar being bent and broken.

The efficiency of the surface of a wall to resist the action of the waves, obviously depends on two circumstances ; first, the power with which the moving particles of the water act on the stones at the surface ; and secondly, the force with which those stones resist removal. The object to be attained is to render the moving power

of the water as small as possible, and the resisting force of the stones as great as possible, relatively to each other.

Without entering into the theory of waves, which involves the highest branches of mathematical analysis, it is sufficiently obvious to daily observation, that the oscillation of each particle of water, in a wave moving freely, is partly vertical, and partly horizontal; that when a sufficient depth of water exists in front of a wall, or a line of cliffs, the mutual action of the direct and reflected waves, produces a series of points of greatest agitation; and that at those points the horizontal oscillation is either null, or so small, as compared with the vertical, that practically the motion of the particles may be considered merely as an oscillation up and down.

A vertical surface is, therefore, that which offers the least possible impediment to the natural motion of the particles of water, under such circumstances, and upon which, consequently, they act with the least power; and a horizontal surface, being perpendicular to the motion of the particles, is that upon which they act with greatest power.

It is also obvious, that when waves encounter a sloping bulwark, or a sloping beach, the vertical part of the oscillation is gradually converted, as the waves proceed, into an advancing and retreating oscillation, parallel to the slope; that being the only direction in which the particles can move, without destroying the surface of the beach, or bulwark; and this oscillation has a powerful tendency to overturn and to remove any obstacle which projects above the line of the slope. Hence it is, that large stones, extracted during storms, from the seaward slopes of breakwaters, have frequently been swept entirely over to the landward side; and from the same cause it also arises, that the coping and upper portions of a curved bulwark, such as that in Fig. 5, are liable to be overthrown, by the concussion of the body of water directed against them, by the lower part of the slope.

The force with which a stone resists removal, is composed of three parts; the first arises from its own weight, and is obviously greater the flatter the slope, and is greatest of all when the surface is horizontal;—the second arises from the pressure of the superincumbent masonry; and this is as obviously greater, the steeper the slope, and greatest in a vertical wall;—the third is the adhesion of the mortar, or cement; and as this depends, to a certain extent, on the pressure from above, it also is greatest in a vertical wall.

These principles appear to be entirely in accordance with the facts which have been narrated.

In such structures as the pitching at the foot of the walls in Figs.

2, 3, and 4, and the lower part of the slope of Fig. 5, the resistance to the action of the waves arises, almost altogether, from the weight of the stones, and therefore increases as the slope approaches the horizontal; but as the moving power, exercised by the particles of water, also increases, it is clear, that the stability of bulwarks so constructed depends altogether on the use of sufficiently large and heavy stones, such as those employed in Fig. 5. Hence, in Figs. 2, 3, and 4, the stones of the pitching not being sufficiently heavy, were partially displaced.

In Fig. 4, the destruction of the slope occasioned the fall of the wall, which rested on it; but in Figs. 2 and 3, where the pitching was not used to support the wall, but merely to protect the foundation, the wall suffered no injury in consequence of its removal.

In Fig. 2, where the pitching was laid on the natural level of the sand, the stones displaced, were deposited near their original site; but in Fig. 3, where the slope was comparatively steep, they rolled down with the receding oscillation.

The walls (Figs. 2 and 3) being vertical, or nearly so, approach the form of section which gives, at once, to the particles of water, the least amount of displacing power, and to the masonry the greatest amount of the resistance, arising from the pressure of the superincumbent materials, and the cohesion of cement and mortar; and they afford an illustration of the stability which may be attained with such a form of section, in a structure built of comparatively small stones.

Owing to the extremely small elevation of the wall (Fig. 2) above the surface of the water, it was necessary that the coping should be sufficiently massive to resist, by its weight alone, any force tending to displace it; but in Fig. 3 such a coping was not necessary, as the top of the wall was above the reach of the action of the waves.

The Author has endeavoured, in drawing general conclusions respecting the construction of sea walls, to avoid going beyond the limits warranted by the facts he has stated. His conclusions may be received with caution, or with dissent; but he trusts that the facts will be considered worth recording.

The Paper is illustrated by five diagrams, showing the section of the several sea walls described, and from which Plate 8 is compiled.

Major-General PASLEY referred to an opinion expressed by him at a meeting of the Institution in 1842,* when he stated, that from "his observations of the action of the sea upon various parts of the

* *Vide Minutes of Proceedings, 1842, vol. ii., p. 130.*