PROCEEDINGS OF
THE INSTITUTION OF
CIVIL ENGINEERS

Water and Maritime Engineering

Proceedings of the Institution of Civil Engineers
Water & Maritime Engineering 148
March 2001 Issue 1
Pages 47–56

Paper 12232
Received 15/12/1999
Accepted 07/09/2000

Keywords:
safety & hazards/sea defences/slabs & plates

Douglas Nichol
Geotechnical Engineer, Engineering Services, Wrexham County Borough Council

John M. Reynolds
Geophysics Consultant, Reynolds Geo-Science Ltd, Mold

Ground-penetrating radar survey to detect sub-slab voids beneath the East Promenade at Rhyl

D. Nichol and J. M. Reynolds

At Rhyl, a tourist resort on the North Wales coast, the East Promenade is susceptible to damage by marine scouring processes. Concealed scour cavities were suspected following the sudden collapse of a segment of the promenade and the recognition of numerous depressions and zones of cracking elsewhere in the concrete pavement. The full threat posed to the integrity of the promenade and to the safety of pedestrians remained uncertain and costly reconstruction was anticipated. Ground-penetrating radar was used along a 260 m stretch of the promenade to determine the full extent of voiding beneath the surface. The geophysical survey delineated the known cavity and, contrary to expectations, demonstrated that the sub-slab voiding beneath the remainder of the promenade was relatively minor. The more subdued radar features encountered were interpreted as minor separation beneath slabs due to consolidation. The results provided a basis for design and construction of effective and inexpensive repairs to the promenade foundations that ensured the public safety.

1. INTRODUCTION

At the coastal holiday resort of Rhyl in Denbighshire, North Wales (Fig. 1), the East Promenade provides pedestrians with a dedicated walkway along the sea front. The promenade also serves a coastal protection function and as such is exposed to marine influences. During stormy weather the promenade is particularly susceptible to damage by marine scouring and cavities may form that pose a geo-engineering hazard for maintenance and pedestrian safety.

The East Promenade lies 0·5 km north-east of Rhyl town centre and National Grid Reference SJ 011821 applies. The problematic length of the East Promenade involves an east-north-east to west-south-west oriented stretch of about 260 m situated between Rhyl Lifeboat Station and the Sun Centre. Here, the promenade averages 6 m wide and the sea wall provides continuous stairway access onto the beach (Fig. 2).

This paper presents a practical case history of a ground-penetrating radar survey designed to investigate a known void and, more importantly, to detect suspected cavities beneath the promenade and provide a basis for formulating the most appropriate remedial strategy.

2. GEOLOGICAL SETTING

Geologically, the central feature of the district is the down-faulted rift valley of the Vale of Clwyd.[1] Within the graben tract at Rhyl, the local bedrock consists of soft, brownish red, cross-bedded, medium-grained sandstones of the Kinnerton Formation of Permo-Triassic age. The red sandstones are overlain in places by heterogeneous till deposits associated with the last glaciation affecting the area during Pleistocene (Late Devensian) time.

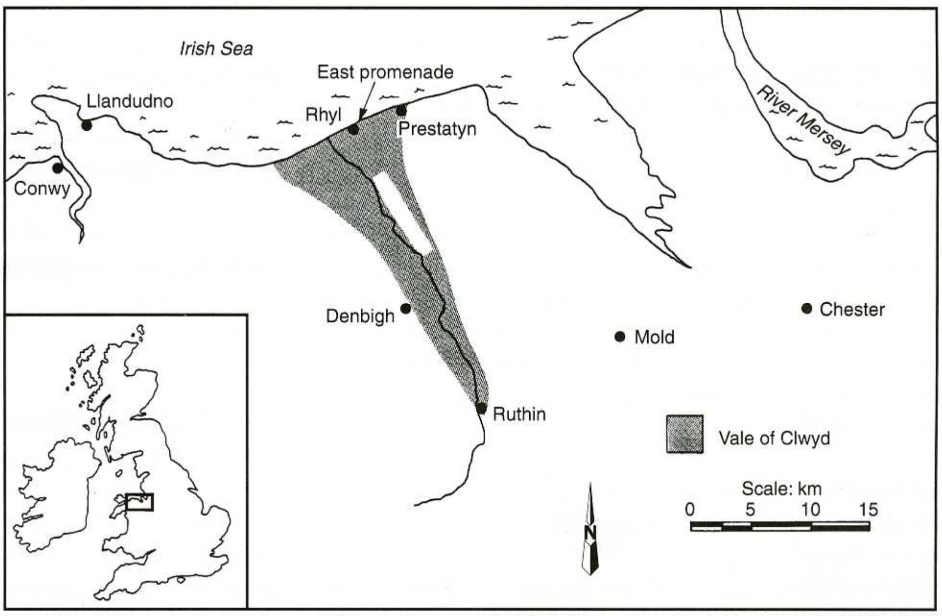

Fig. 1. Orientation map

Fig. 2. The East Promenade at Rhyl looking westwards. Ground-penetrating radar survey in progress, 17 April 1998. The mountainous terrain of Snowdonia forms the background. Rhyl Lifeboat Station lies in the middle distance and the Sun Centre is situated to the left of the picture. Photograph by Douglas Nichol

Rhyl is situated at the mouth of the River Clwyd and alluvial clays, silts, sands and gravels together with beds of peat underlie the extensive, low estuarine flats. The relatively thick drift (superficial) cover along the coastal fringe comprises Holocene deposits associated with storm beaches, shingle spits and wind-blown sand-dunes.

In the vicinity of the East Promenade, blown sand forms low to gently undulating dunes on the landward side of the promenade and spreads of beach and intertidal sands occupy the seaward side. The present-day beach deposits of sands and gravels are subject to easterly longshore drift.

3. HISTORICAL BACKGROUND

During the nineteenth century, a continuous line of sand-dunes ranging up to 10 m high existed along the coastline from the estuary of the River Clwyd for almost 11 km towards Prestatyn.[2] However, the original concrete sea wall at Rhyl, built between 1907 and 1913, triggered extensive marine erosion that destroyed much of the line of dunes.[3] Indeed, the severe effects of marine scouring at the eastern end of the old sea wall necessitated the construction of more robust sea defences. These later measures included the seawards extension of the sea wall to form the present-day configuration of the East Promenade.

Rhyl is perhaps the most famous seaside town in North Wales, with 5 km of sandy beach backed by wide elegant promenades. The East Promenade forms an integral part of the elaborate seafront complex. It was designed to provide holidaying visitors with a level walkway for seaside perambulation as well as easy access between the beach and the other tourist facilities along the sea front.

Much of the remaining dune formation has been levelled and landscaped as the resort has developed. Progressive upgrading over recent years includes the addition of paving, seating, windbreaks and rain-shelters as well as modern indoor facilities such as the Sun Centre, Sky Tower and Sea-Life Centre.

Maintenance works are usually required on the East Promenade following either stormy weather or high spring tides. Typically, these include removal of sand accumulations and minor repairs to drains, groynes and sea walls.

4. COLLAPSE EVENT

On 9 April 1998, a segment of the East Promenade failed spectacularly during a maintenance programme. The collapse revealed the existence of a major cavity below the running surface of the promenade. The hole in the slab measured 1·8 × 2·2 m and the void ranged up to about 1·5 m deep (Fig. 3).

The immediate response to the collapse involved safety measures to protect pedestrians using the promenade. Loose sand was tipped into the hole to fill the void and a barricade was erected around the hazard.

Subsequently, a visual condition survey of the concrete slabs along the East Promenade disclosed numerous shallow depressions and areas of water ponding as well as zones of longitudinal, radial and alligator cracking. Displacements of up to 10 mm were recorded across the cracks. These surface observations prompted concern about the potential for unknown cavities that could produce further collapses or disrupt the surface environment. Accordingly, as a matter of prudence, a ground-penetrating radar survey was commissioned as the most rapid and reliable means of assessing the extent of subsurface voiding beneath the promenade. Although not significantly cheaper than traditional intrusive techniques such as coring, radar plots provide the benefit of continuous imaging rather than spot information.

5. SITE INVESTIGATION

The initial phase of the geophysical investigation involved setting out a series of five parallel survey transects along the East Promenade. From the top step above the beach, the survey lines were spaced at 1 m intervals across the width of the promenade. Short transverse and supplementary lines were also surveyed. For logistical purposes, the length of the survey area was divided into ten separate blocks ranging up to 30 m in length (Fig. 4).

Fig. 3. Collapse feature (after infilling with sand for reasons of safety) on East Promenade, Rhyl, 17 April 1998. Photograph by Douglas Nichol

surface antenna.[4] In this case, an SIR-2 radar system with a single antenna was deployed for the survey works. The instrument was dragged over the ground surface along each of the designated survey lines.

Trial surveys were performed using 400 and 900 MHz antennae in order to gauge the best signal penetration, resolution and signal-to-noise ratio at this specific site. The trials were conducted over the position of the known cavity and the optimum antenna selected based on visual inspection of the field radargram printouts generated by the SIR-2 instrument. The trials demonstrated that the 900 MHz antenna was the most appropriate configuration in this instance.

In ground-penetrating radar applications, radio-frequency pulses are transmitted into the subsurface and reflections from materials with differing electrical properties are received at a

Radar survey sweeps were carried out along the promenade with radar data acquired continuously along each survey line. Position fix marks were recorded at an interval of 1 m.

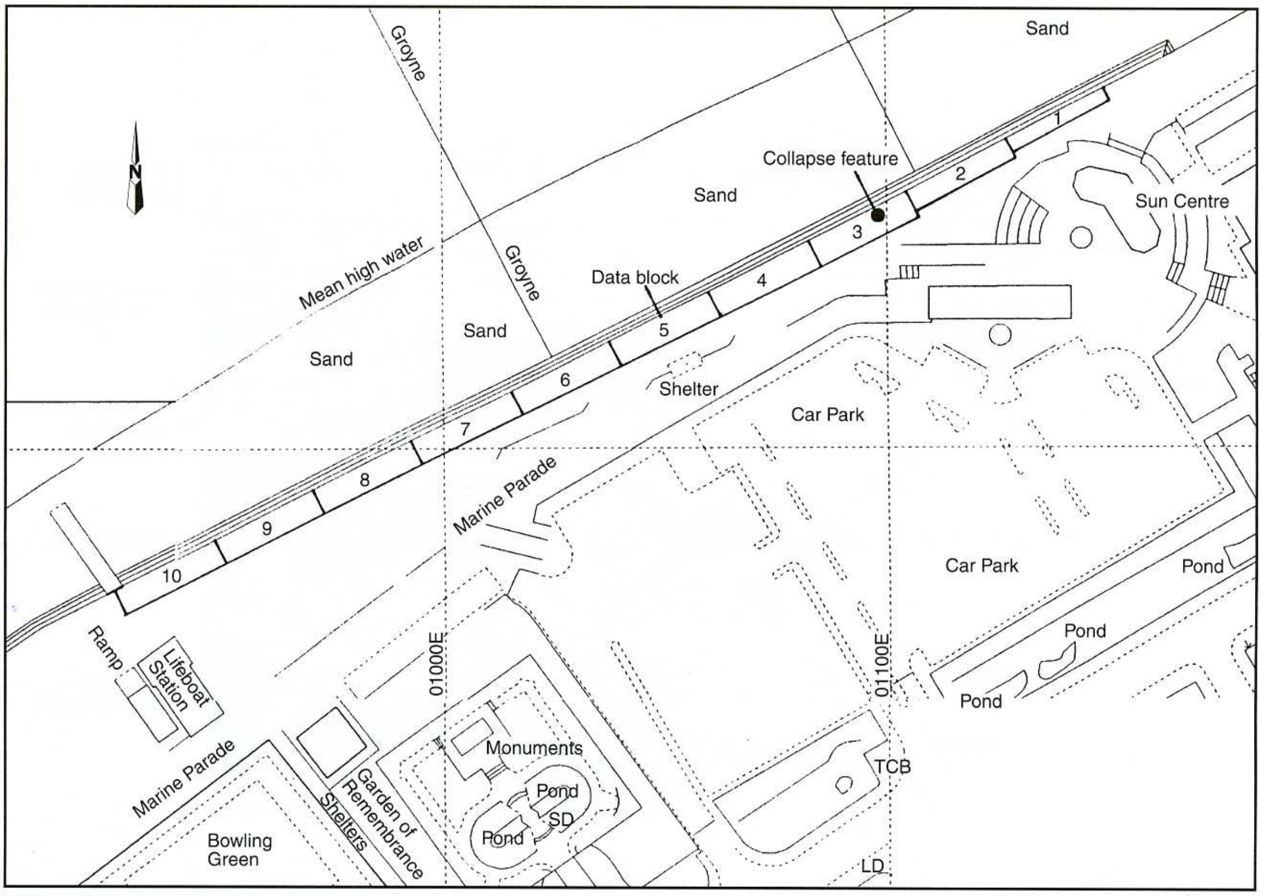

Fig. 4. Survey location map

Hard-copy printouts of the raw radar data were obtained in the field on thermal paper. The raw field records were also stored onboard the SIR-2 instrument in digital format and later downloaded onto magnetic medium for transfer to a separate computer.

6. INTERPRETATION

Numerous features were located along the East Promenade. Typical radargram printouts are illustrated in Figs 5, 6 and 7 with annotations to indicate the correlations. The radargrams depict horizontal profiles measured as a function of two-way travel time (TWTT) with a range of 20 nanoseconds (ns).

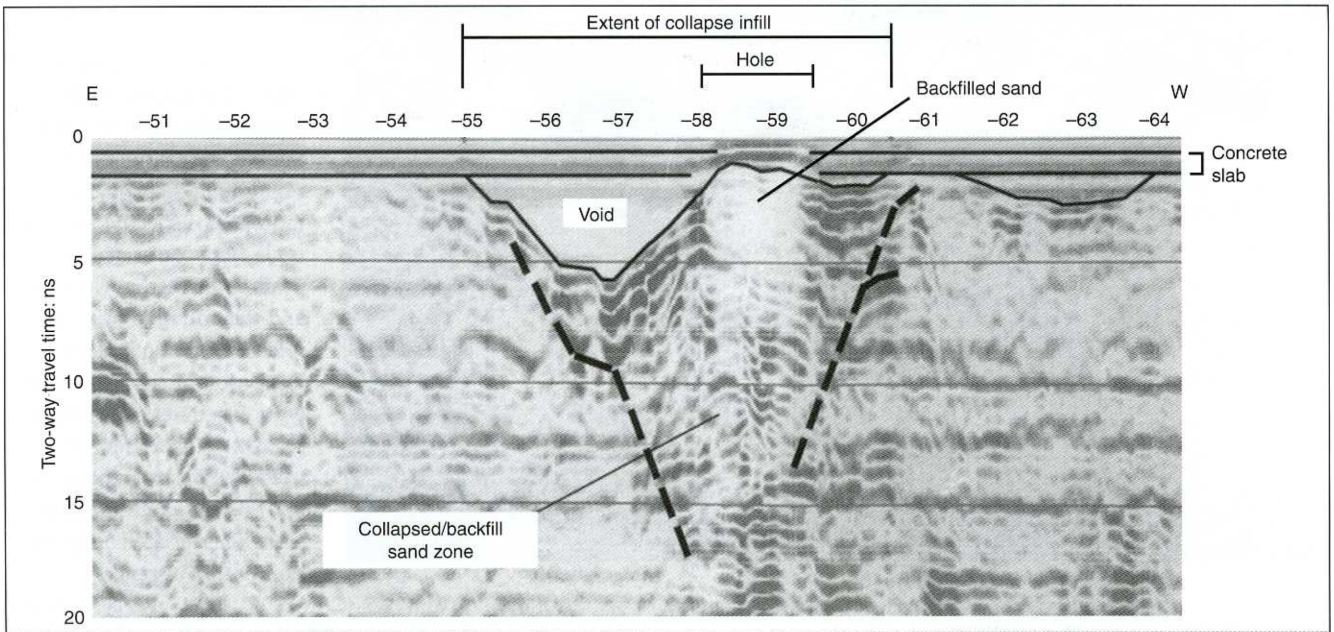

Fig. 5. Radargram section 0·5 m from edge of promenade at position −50 m to −64 m

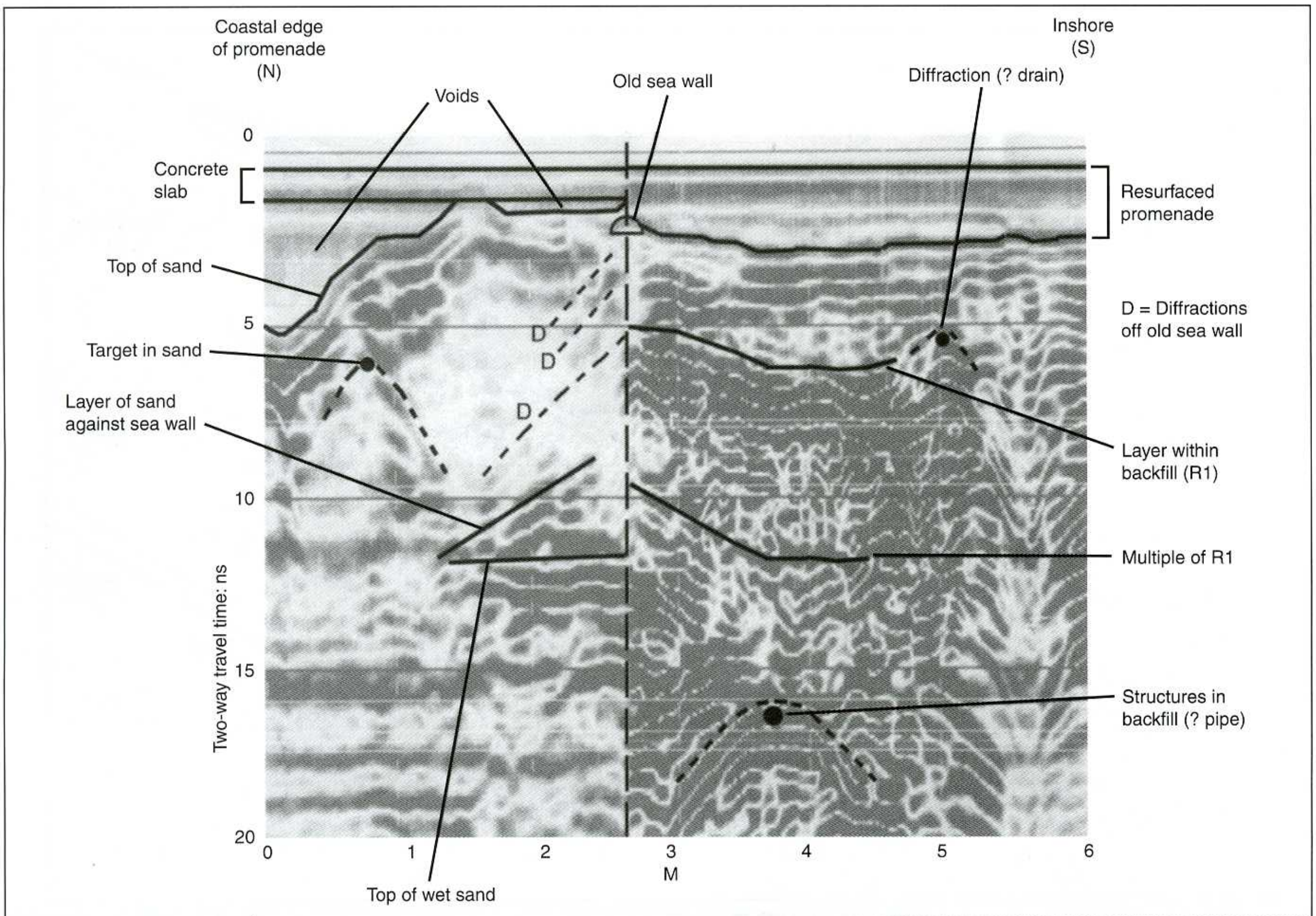

Fig. 6. Transverse radargram section at position −57 m

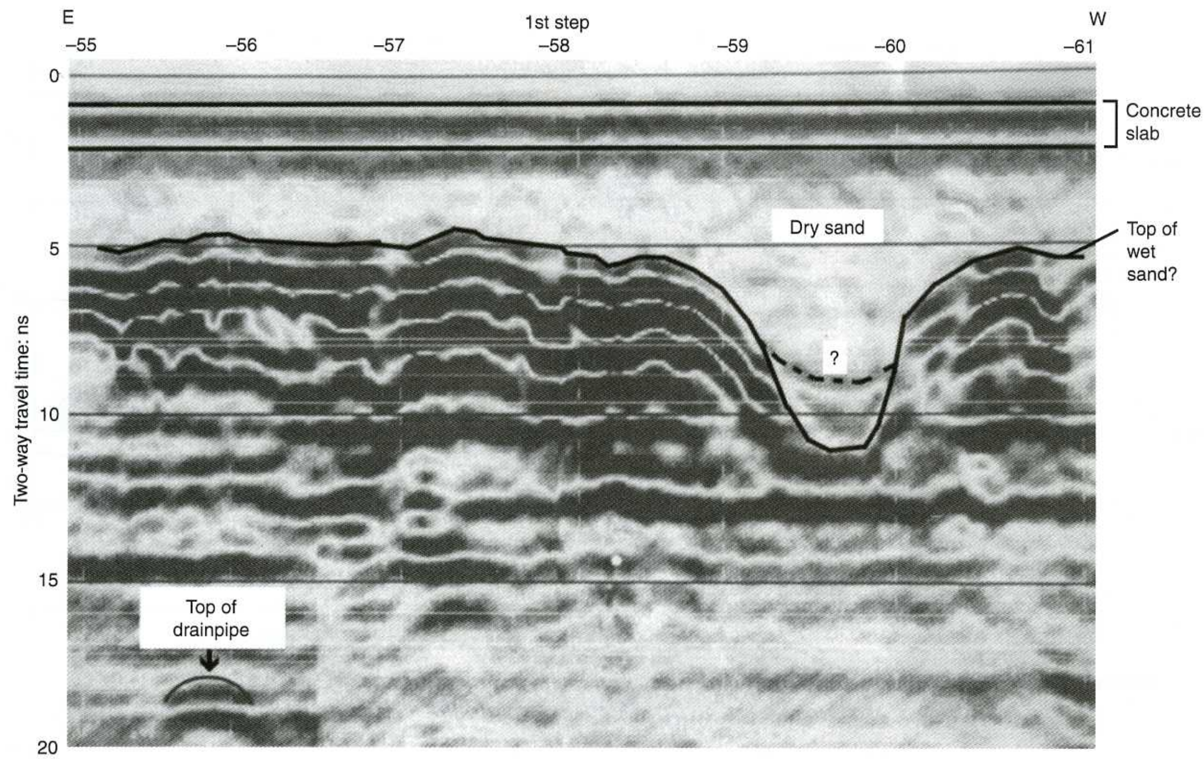

Fig. 7. Radargram section along the top step at position −55 m to −61 m

As a general guide to actual depth below the surface, using a radiowave velocity of 0·3 m/ns for air, each 1 ns of TWTT equates to a distance of 0·15 m. A radiowave velocity through sand of 0·1 m/ns was assumed in order to estimate depths to buried targets within the sand fill beneath the concrete slabs. This postulated radiowave velocity was cross-checked at a drainpipe which discharges through one of the steps near the collapse feature. The drainpipe provided a depth control measurement and here a radiowave velocity through the sand of $0{\cdot}1 \pm 0{\cdot}02$ m/ns was determined. Thus, the radargram examples have a maximum depth of penetration of around 1·3–1·5 m.

The methods and scheme of interpretation used are analogous to those employed in the interpretation of continuous seismic reflection profiling.[5,6] In essence, significant reflections were identified on the basis of signal strength and coherence. In addition, a phase reversal in the waveform can be observed where an air void lies immediately below the concrete slab. Diffractions arising from point sources were also identified.

6.1. Known cavity

The radargrams generated at the collapse site depict a uniform, featureless signal that corresponds with the air-filled void (Fig. 5). In addition, the pile of loose sand backtipped into the hole forms a conspicuous anomaly. Several bright reflections appear below the cavity and probably represent structures associated with subsidence of the original sand mass. A second, smaller void is also evident between −61 m and −64 m.

The transverse radargrams across the area with the known cavity also distinguish the air-filled voids as well as revealing details of the ground behind the original sea wall (Fig. 6). The character of the radargrams diversifies in the vicinity of the old sea wall and several features are noteworthy. From the surface, the ground-coupled waves change form and lengthen relative to that in the rotten concrete, and the deeper areas to the south of the old sea wall display greater reflectivity than the sand mass to the north. In addition, the presence of the old sea wall generated a series of diffractions (labelled D in Fig. 6) and two intense reflections. The topmost reflection inclines upward towards the sea wall and resembles an accumulation of sand banked up against the wall. The lower reflection appears flatter and may be due to wet sand. Finally, strong diffractions occur at about 1·1 and 2·3 m south of the old sea wall and indicate the presence of internal structures such as drains or pipes.

To delimit the known cavity, five supplementary radargrams were acquired along a short stretch of the steps (−55 m to −61 m) adjacent to the existing hole. Fig. 7 illustrates the radargram obtained along the top step. The concrete steps measure approximately 0·1 m thick. They are underlain by a featureless zone that is interpreted as dry sand. A marked reflection on the radargrams at TWTT of 5 ns is interpreted as the top of wet or damp sand. A peculiar depression appears between −59 m and −60·5 m on all of the radargrams acquired over the steps. Its physical significance remains uncertain. Finally, a strong diffraction exists on the radargrams at depth at −55·8 m and correlates with a known 0·2 m diameter drainpipe that discharges through the seventh step from the top.

6.2. The promenade

The findings of the ground-penetrating radar survey along the entire East Promenade are presented in Fig. 8 as a series of block maps labelled 1–10 inclusive. The maps depict interpreted void heights from zero through to over 0·45 m. The positions of prominent diffractions are marked, together

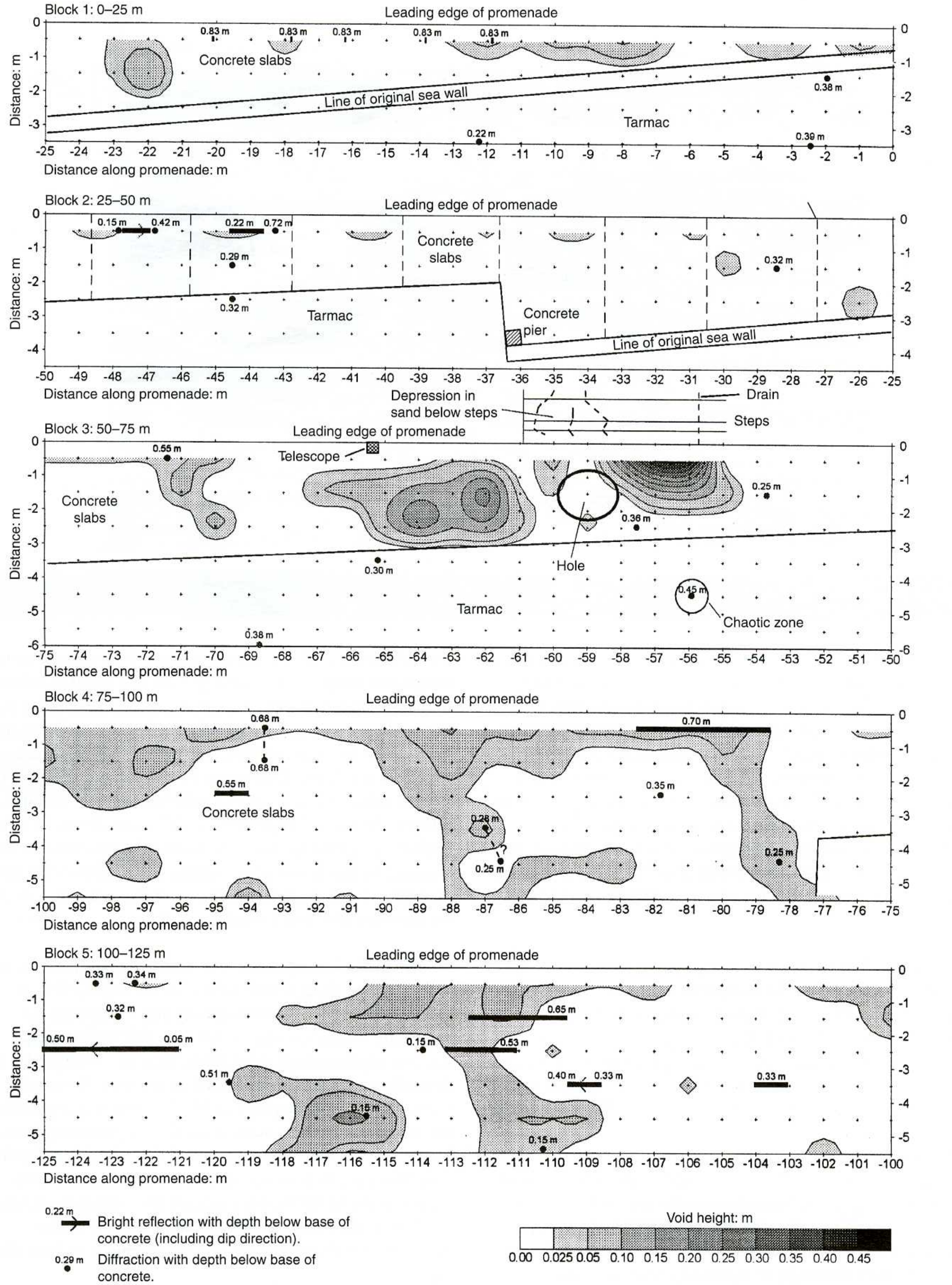

Fig. 8. Model of interpreted void dimensions along the East Promenade (continued opposite)

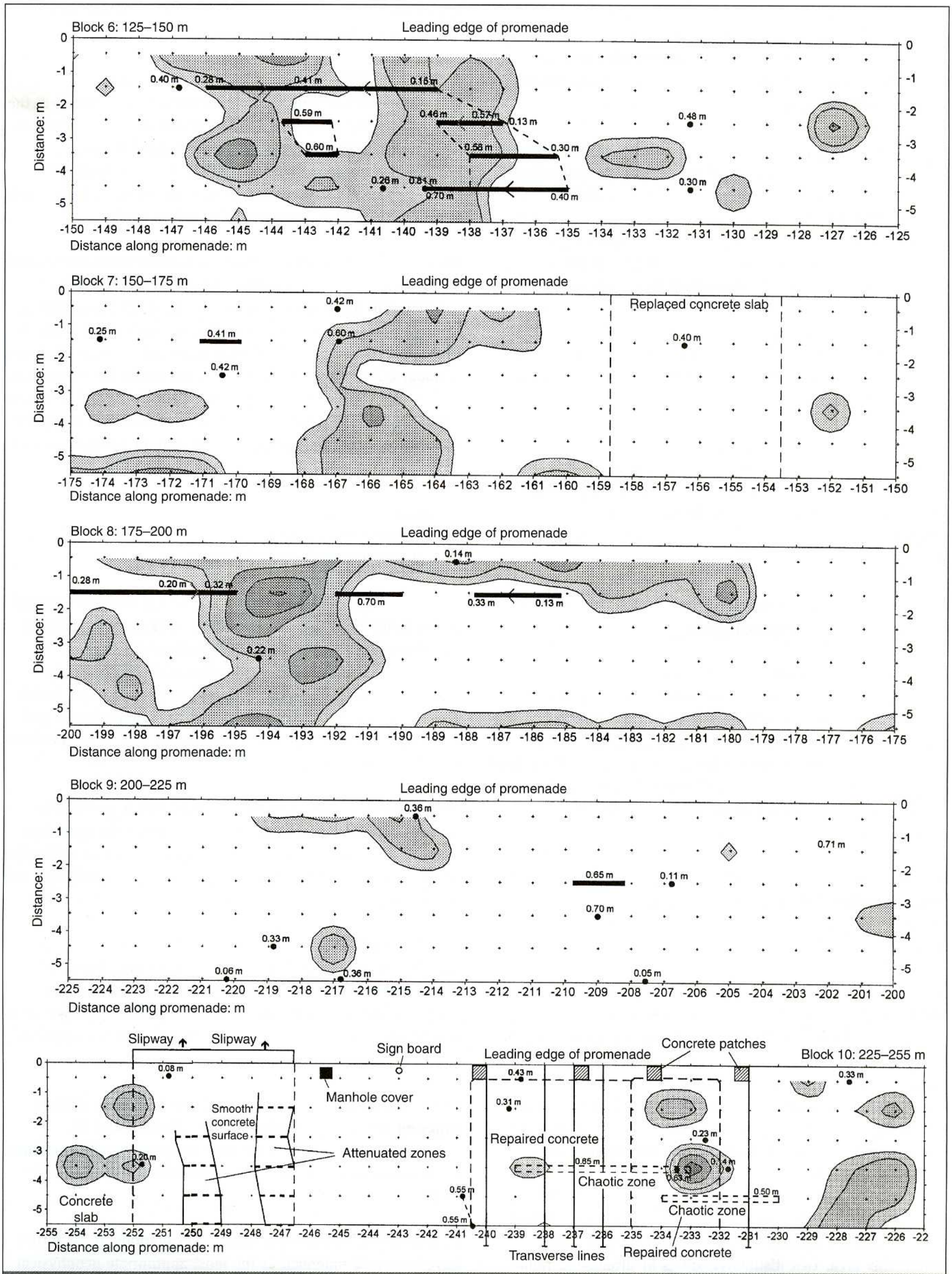

Fig. 8. continued

with the corresponding interpreted depth below the base of the concrete slab using an assumed radiowave velocity of 0·1 m/ns. Bright reflections are also marked, together with their interpreted depth below the base of the concrete. Dipping reflections have an arrow pointing in the direction of apparent dip.

The engineering significance of void heights of less than 0·05 m is difficult to surmise. Although airgaps undoubtedly exist below the concrete, such small sizes are difficult to resolve from the raw radargrams with any great accuracy. Consequently, the physical significance of void height is taken as $\pm 0{\cdot}05$ m and so those voids having heights greater than or equal to 0·1 m are considered to be physically meaningful.

Noteworthy features from Fig. 8 include the absence of voids under the tarmac area, the concentration of void development alongside the seaward edge of the concrete slabs and within the middle of certain slabs.

In block 3, the position of the known cavity is labelled. The void size appears minimal at the site of the collapse because the hole was backfilled with sand to the same level as that of the concrete slab. However, areas of void remain on both sides of the site.

In block 6, two features require explanation. First, the blocky distribution of the interpreted voids; this pattern correlates with individual concrete slabs which typically measure about 3 m wide. Second, the inclined reflections which dip westwards around the position −137 m; these have the appearance of a dipping sand-dune face and may represent a former natural surface that has been built over. Conceivably, the inclined reflections relate to a former collapse area where sand has been backfilled into a cavity but this explanation seems difficult to reconcile with the absence of any significant sub-slab voiding greater than the 0·1 m detected.

In block 8, another area of shallow sub-slab voiding is apparent around position −194 m and approximately 1·5 m from the edge of the promenade. This area also underlies a single concrete slab.

In block 10, two slabs of concrete have previous repairs and here the radargrams reveal two noteworthy features. First, a possible cavity with a void height of up to 0·2 m occurs at position −233 m and approximately 3·5 m from the edge of the promenade. Second, narrow zones of chaotic reflections are present between depths of 0·5 and 0·65 m below the base of concrete slabs. These features may relate to former collapse features that necessitated the repairs to the slabs.

\Also in block 10, the slabs between Rhyl Lifeboat Station and the slipway have a smooth concrete surface and, within this area, two distinctive zones of attenuated radar signals are evident on the radargrams at shallow depths around positions −247 m and −250 m. It is speculated that these two zones relate to the axle width of the trailer used to deploy the lifeboat. The weight of the transporter carrying the boat may apply sufficient load to the ground to reduce the local soil moisture content and thereby reduce the dielectric contrast between the concrete surface and the material immediately below it.

7. DISCUSSION

This ground-penetrating radar investigation commenced in the anticipation that extensive voiding would be detected beneath the East Promenade. The survey was intended to pinpoint numerous voids and reveal the extent of the problem. The absence of substantial voiding proved an unexpected result and obviated the need for major reconstruction works.

The findings of the survey redirected attention onto the original collapse and the reasons behind the event. On the basis of concrete slab thicknesses revealed by the ground-penetrating radar as well as direct measurements, the slab at the collapse site varied up to 0·15 m thick compared with a typical thickness of about 0·2 m elsewhere along the promenade. Moreover, the slab at the collapse site seemed somewhat friable and at a more advanced stage of deterioration than that elsewhere along the promenade. Accordingly, the collapse may be attributable to a combination of

(*a*) thinned concrete
(*b*) cracked rotten concrete
(*c*) the presence of the sub-slab void.

Subsequent excavation of the known cavity provided physical access to the nearby drainpipe which outfalls on the seventh step immediately to the east of the collapsed area. The condition of the sand around the pipe was observed to be compacted and undisturbed. In addition, an inspection trench was excavated on the beach to uncover the buried steps and lower sea wall adjoining the collapsed area (Fig. 9) but here too, no defects were identified.

Although the formation of the sub-slab void is ascribed to marine scouring, uncertainty remains whether sea water has infiltrated the structure through the gaps in the steps or if water has drained through the cracks in the surface concrete slab and washed sand out through the gaps between the steps.

8. REMEDIATION

Remedial works carried out on the known cavity involved demolition and removal of the damaged slab, excavation of loose infilling materials and replacement with compacted sand and finally, construction of a new concrete slab incorporating steel mesh reinforcement.

Minor repair works were performed along severely cracked zones on the running surface around blocks 4 and 10. Inspections carried out during these repairs generally confirmed the dimensions of the sub-slab voids and verified the radar results.

Further ground-penetrating radar investigations in the future have been recommended as the most appropriate geophysical technique for monitoring of sub-slab void development.

9. CONCLUSIONS

At Rhyl, Denbighshire, a segment of the East Promenade collapsed due to the presence of a concealed cavity beneath the concrete pavement. The voiding was attributed to scouring and

Fig. 9. Inspection trench on the beach adjacent to the collapse area. Excavation in progress, 3 June 1998. Photograph by Douglas Nichol

0·1 m with a maximum of 0·18 m. This voiding may be explained by settlement of the sand infill used within the promenade foundations.

The ground-penetrating radar survey has also indicated several other sub-surface features including the old sea wall, variations in foundation material types and conditions and details of the structures beneath the promenade to a maximum depth of 1·5 m.

The survey proved that the extent of the potential problem at the Rhyl East Promenade was much less than anticipated. The cavity associated with the collapsed zone was the only significant one found. The reasons for the hole appearing at this location are possibly related to thinned concrete, cracked rotten concrete and the presence of the sub-slab void. However, the origin of the cavity remains open to question.

The ground-penetrating radar survey provided the comprehensive understanding of the site needed to formulate a strategy to efficiently and economically repair the foundation support to the promenade and thereby ensure the safety of pedestrians.

wash-out by marine processes. A condition survey of the pavement surface revealed numerous depressions and areas of cracking indicative of extensive sub-slab voiding. Since the presence of such cavities posed a potential threat to the safety of pedestrians, substantial and expensive reconstruction of the promenade appeared likely.

A ground-penetrating radar survey demonstrated that cavities beneath the promenade can be imaged using a 900 MHz antenna with an SIR-2 instrument. The survey successfully delimited the extent and dimensions of the known cavity beneath the promenade. Elsewhere along the promenade, the radar technique rapidly demonstrated the absence of any other similarly sized void. Only areas of small-scale sub-slab voiding were detected, with vertical dimensions predominantly less than

10. ACKNOWLEDGEMENTS

Field geophysical surveying was carried out by Geo-Services International (UK) Ltd in accordance with design, supervision and interpretation by Reynolds Geo-Sciences Ltd. This paper is published with the permission of the Director of Technical Services, Denbighshire County Council.

REFERENCES

1. WARREN P. T., PRICE D., NUTT M. J. C. and SMITH E. G. Geology of the country around Rhyl and Denbigh. *Memoir of the Geological Survey of Great Britain*, Sheets 95 and 107 (England and Wales). HMSO, London, 1984, 217 pp.
2. STRAHAN A. The geology of the coasts adjoining Rhyl, Abergele and Colwyn. *Memoir of the Geological Survey of Great Britain*. 1885.

3. Neaverson E. Coastal changes around Liverpool Bay since the ice age. *Proceedings of the Liverpool Geological Society*, 1947, 19, 184–209.
4. Reynolds J. M. *An Introduction to Applied and Environmental Geophysics*. Wiley, Chichester, 1997, 796 pp.
5. McQuillin R., Bacon M. and Barclay W. *An Introduction to Seismic Interpretation*. Graham and Trotman, London, 1983, 287 pp.
6. Reynolds J. M. and Taylor D. I. The use of sub-surface imaging techniques in the investigation of contaminated sites. *Proceedings of the 2nd International Conference on Construction on Polluted and Marginal Land, Brunel University* (Forde M. C. (ed.)), 30 June–2 July 1992, 121–131.

Please email, fax or post your discussion contributions to the secretary: email: sismey_h@ice.org.uk; fax: +44 (0)20 7799 1325; or post to Helen Sismey, Journals Department, Institution of Civil Engineers, 1–7 Great George Street, London SW1P 3AA.