1. Introduction
Case studies describing landslide investigations are a valuable resource. They provide information on the type and mechanics of the landslides of their geological area, and hence are a useful guide for studies of similar landslides in the same area or in similar geological conditions. Case studies dealing with remedial works are also of interest, particularly where the effectiveness of the remedial works is reported.

This paper presents a landslide case study which describes the investigations and remedial works for a landslide on the east coast of Northern Ireland, highlighting those aspects of the study that are thought to be of particular interest. It can be demonstrated that, though the landslide was partly a reactivation of a much older landslide, it also involved a significant mass of material that appeared not to have been previously part of the landslide. This resulted in the landslide being, in part, a first-time event, involving the simultaneous development of more than one sliding surface, and raising fears of a possible accelerating movement as a result of progressive failure of the brittle, strain-softening stiff clay involved. Additionally, movement observations show displacement rates to be much greater at the crest of the slope than at the toe. Another interesting result relates to the remedial measures, which were straightforward: the removal of the load placed at the crest of the slope that had caused the movement of the landslide. The effect of this load removal was monitored by inclinometers, and the observed movements are reported, allowing the effectiveness of the remedial measures to be assessed.

Substantial movements of the slope took place in 1977-78, and it is these movements and other events during the period 1977-80 with which this paper is concerned.

2. The Magheramorne Landslide
The Magheramorne landslide is located a few kilometres south of the town of Larne, on a coastal slope running down to Larne Lough, a coastal inlet which opens to the Irish Sea; see Fig.1. At the foot of the slope are a major road (the "Coast Road") and a railway, both of which run on level ground about three to four metres above sea level. Away from Larne Lough, to the west, the slope steepens and rises to about 38 m above sea level (a.s.l.; Belfast datum) over a distance of 150 m, to the foot of a large man-made tip of rock waste. This tip has side slopes inclined at about 35°, and rises to about 100 m a.s.l. It is referred to subsequently as either the "Works Tip", or simply "the tip". The rock waste is from a quarry excavated through Tertiary Basalt to Cretaceous Chalk, a particularly pure limestone that was excavated for cement manufacture. The Basalt had no economic value, and was removed to allow the Chalk to be excavated. The cement works is now closed.

Downslope from the tip the natural ground varies in inclination, being about 12° immediately below the tip,

![Fig.1 Plan of the Magheramorne landslide, and the location of the site. The Line of Section is that shown in Fig. 3.](image-url)
reducing to around 8° near the Coast Road. Much of the area below the tip is hummocky grassland. An oblique aerial photograph showing the general layout of the area is shown in Fig. 2.

In 1973 it was suggested that operations at the quarry were causing damage to two buildings, a Post Office and a bungalow, and also to a road (“Ballylig Road”) that formed the downslope boundary to the area of the tip, see Fig. 1. An extensive investigation of the cause of the damage to the two buildings was carried out in 1978, and this is described below.

2.1 Geology

A stratum of Basalt, up to about 110 m thick, is the highest deposit in the area, though it does not occur on the slope with which this paper is concerned. Under this lies the Chalk (27 to 12 m thick), below which is up to six metres of Glaucocitic Chalk, which is unsuitable for cement manufacture, and was not worked in the quarry. The level of the base of workable chalk is shown by other geological studies to be at about 33 m a.s.l. The Glaucocitic Chalk in turn overlies about 16 m of Greensand (glaucocitic sands and sandstones), which are particularly variable in thickness, and locally may be in total as much as 25 m or as little as four metres. Below the Greensand lies the Lias (of Jurassic age), which is either a stiff clay or a soft, grey, silty mudstone with calcareous horizons and thin limestones. This is the lowest horizon with which we are concerned.

In addition to the “Solid” deposits discussed above, superficial deposits also occur. These are of two types, either a fragmented version of the bedrock sequence, though often less thick than when found in situ, but with the various strata still in correct downward sequence. Alternatively, the superficial deposits may be a random, intimate mixture of broken bed-rock fragments set in a matrix of softer material. The former deposit is termed “Landslip debris”, the latter “Head”. Often there is a graduation between the two deposits, and no firm distinction between the two can be drawn. To complicate the problem, fill derived from the quarry workings, and thus composed largely of basalt and chalk, sometimes with a clayey matrix, also occurs on the slope. This fill material is difficult to distinguish from Head.

At the foot of the slope, Glacial Till (fragments of predominately local material such as basalt and chalk set in a matrix of grey Lias-derived clay, deposited by Pleistocene ice) was encountered, overlain by almost three metres of Estuarine Clay of Recent age. This stratigraphic sequence is summarised in Table 1.

2.2 History of the slope.

A direct consequence of the presence of the relatively weak Lias, which outcrops at the foot of many of the Northern Ireland coastal slopes, is that, where either coastal or glacial erosion has steepened the slope sufficiently, landslides have developed. The vast majority of these landslides appear to be stable at the present day, suggesting that these landslides are of considerable antiquity. It is assumed that they originated as a result of the highly erosive environment of the last glacial period (Stephens 1958). It seems probable that the Magheramorne slope, too, has been formed by either glacial or marine erosion, or by a combination of the two processes.

There is a record of a landslide at the site at the end of the 19th century. This seems to have been a renewal of movement of a much earlier landslide, reacti-
vated either by the placement of quarry waste on the slope, or perhaps by exceptional rainfall. This movement is probably responsible for the topographic freshness of the landslide toe, which forms an obvious feature about a metre high (Fig.1). There are no other records of movement of the slope until April 1973, when it was suggested "that blasting from the quarries had caused damage to private property [the Post Office and bungalow] nearby" (Anon., 1973). Cracks and structural movements of up to five millimetres were reported, indicating a further renewal of movement of the landslide.

The date of commencement of construction of the Works Tip at the crest of the slope is unknown. It apparently stood at about 89 m a.s.l. for some years prior to 1973, when tipping recommenced, though aerial photographs taken in 1975 show that little further material had then been added. By 1977 the crest of the tip was at 98 m a.s.l. Tipping ceased in December 1977.

The damage to the buildings became noticeably more serious in late spring 1977, following the renewed tipping on the Works Tip and the 1976-77 winter, which was wetter than average.

3. Investigation of the landslide

The plan of the area (Fig.1) shows the boundaries of the landslide. A clear "toe" feature, well seen in aerial photographs, separates hummocky ground above from the smoother, flatter ground adjacent to the Coast Road. A trial excavation showed that the toe feature was the result of landsliding, with movements in excess of one metre, perhaps considerably more. There was no evidence of movement of the Coast Road, which appeared to be quite stable. The western lateral boundary of the landslide could be seen as an obvious crack in Ballylig Road, and by corresponding displacement of the adjacent wall. The eastern boundary of the landslide, also crossed by Ballylig Road, could be inferred by reference to the limit of minor movements of the road surface.

In January 1978 cracks were observed 20 m back from the crest of the Works Tip, which delimited an area where subsidence had occurred. It was to be expected that settlement of the loosely tipped rock waste would occur, but the coincidence of the area of greater settlement of the part of the tip immediately above the general landslide area showed that this part of the tip was involved in the overall landslide movement.

Both rotary cored boreholes and air-flush percussive drilling were used to establish the sub-surface details of the landslide, shown in Fig.3. All the cores were split for detailed examination, and were logged for both lithology and discontinuities. Further geological information on the line of section was provided by a number of air-flush percussive boreholes, which gave an approximate record of the strata encountered. Water levels encountered in the boreholes were noted, and piezometers were installed.

Documentary evidence recorded that the tip had been placed over an earlier quarry excavated in the Chalk, as shown in Fig.3, though its exact position is not known.

The extent of the landslide movement was clearly established by slope inclinometers, which were installed in a number of boreholes. Movement was recorded at greatest depth in borehole C1, at 25 m; both this borehole and borehole C2 clearly show movement at two different levels, though only one level of
movement, becoming progressively less deep downslope, occurred in boreholes C3 to C6. Borehole C5 showed only tiny (± 3 mm) apparently random movements at the limit of discrimination of the inclinometer, consistent with its position in stable ground just beyond the toe of the landslide. Fig. 4 shows the detailed slope inclinometer records for boreholes C1, C2 and C3.

The considerable depth of movement recorded in borehole C1 immediately adjacent to the Works Tip established beyond doubt that the tip was involved in the landslide movement.

The interpretation of the landslide section, Fig. 3, is the simplest possible based on the borehole logs and the inclinometer data. There is no doubt that the section is in reality more complex than shown, probably being composed of many successive circular arc segments, each originally having slipped independently, but now moving together as a block. However, there was also considerable internal compression, since the up-slope portions of the landslide were moving much faster than the toe. Such an observation is not unusual, though there appear to be little data reporting this phenomenon in the literature. The movement records are shown in Fig. 5, in which the average settlement of the crest of the Works Tip, the average inclinometer movements, together with the lateral movements of the Post Office, are compared. It is seen that during this period the landslide movements become progressively less from crest to toe, with more than three metres subsidence at the crest of the tip, but only about 10 mm lateral displacement of the Post Office at the landslide toe.

3.1 Piezometric data

The piezometric surface was determined using Casagrande-type piezometers, composed of 10 mm diameter plastic tube with a porous-stone tip placed at or close to the slip surface. The porous tip was set in the borehole in a “sand pocket” of one metre nominal length, the remainder of the hole being sealed with cement grout so that the water level in the plastic tube reflected the pore pressure in the ground at the depth of the piezometer tip. They were installed during April-May 1978, and readings were made at regular intervals until the end of August 1978. Most piezometers had come to equilibrium by the beginning of July 1978.

It was noted that the shallower piezometers, particularly those located in the Greensand, indicated higher piezometer levels than did the deeper piezometers.
This “perched water table” effect is a situation commonly encountered in slopes, resulting from the fact that the permeability of the ground, even with a single soil type, becomes less with increasing depth. The effect is exaggerated in this case as a result of the relatively permeable Chalk and Greensand landslide debris which overlies the much less permeable Lias. The airflush percussion holes encountered water levels in the landslide that were comparable with the piezometer readings, as seen in Fig. 3.

3.2 Rainfall data

With the climatic conditions generally experienced in Great Britain and Ireland, ground water levels generally reach their maxima during the winter months (November-March), and landslide piezometric levels can be expected to be higher than usual in winters that are wetter than average. In relation to the average winter rainfall for the period 1916 to 1978, from 1961 to 1978 particularly wet winters occurred in 1965-66 (139% of average), 1966-67 (122%), 1973-74 (130%) and 1976-77 (123%). No movements of the Magheramorne landslide were reported during 1965-67, but some movement occurred in early 1973 following a rather dry winter (85%), and again in early 1977. Movement continued throughout 1977 and 1978, in a period of no more than average rainfall. Thus the landslide movements show no particular association with wet periods, but correlate well with the increasing height of the Works Tip following the renewal of tipping in 1973.

4. Stability analyses

The overall piezometric surface relating to the slip surface used for the various stability analyses is shown in Fig. 3, based on the piezometer readings during July-August 1978, at a time when the landslide was actively moving. Where the piezometer tips were located at the slip surface the indicated equilibrium piezometric level has been used directly: where two piezometers at the same location straddle the slip surface an intermediate piezometric level was used. The Works Tip has been assumed to be highly permeable, and that the piezometric level was correspondingly low.

A number of stability analyses have been carried out using the slope section, Fig. 3. The “Conventional Method” of analysis has been used (e.g. Skempton and Hutchinson 1969): more sophisticated methods were thought not to be appropriate as the exact mechanism of movement, particularly in the region of the Works Tip, was not known. The unit weights assumed were 21 kN/m$^3$ for the rock-waste tip material, and 18 kN/m$^3$ for the remaining landslide material. The analyses help provide the answers to the following questions. Was the tip responsible for the movements of the landslide? Why was the upper part of the landslide moving faster than the lower portion? What are the most appropriate stabilisation measures?

Fill, composed of rock waste from the quarry, overlies much of the slope, as can be seen in Fig. 3. It is probable that this fill (though its placement on the slope may have been responsible for the 19th century movement of the landslide) was placed in relatively small quantities, and over a considerable period of time, and may be assumed to provide a drained, rather than an undrained loading.

The various stability analyses consider different segments of the landslide, designated AA’ A” A”’ B’ C, BB’ C, etc., as shown in Fig. 3. It is first necessary to establish whether peak or residual soil strength parameters are appropriate. Where a landslide movement occurs for the first time, and the soil has not previously been sheared, it can be anticipated that maximum or peak strength parameters are appropriate. When movement occurs in a clay soil, a shear surface forms as a result of the orientation of the component soil particles along the plane of movement. As a result, the soil strength drops from peak to residual strength, which is reached once the soil particle reorientation is complete. The residual strength controls the stability of a landslide once its internal geometry has fully evolved. Since the Magheramorne landslide was at least in part the reactivation of an earlier landslide, the residual strength is of importance. Residual strength failure envelopes are usually slightly non-linear, exhibiting a small cohesion intercept ($c'$), together with an angle of shearing resistance ($\phi'$) that reduces with increasing stress level. For simplicity it is assumed here that $c' = 0$, and that a single value of $\phi'$ applies, irrespective of stress level.

The sequence of analyses commences by examining the magnitude of $\phi'$ for the portion of the landslide shear surface in the Lias, by considering the stability of segment BB’C. This includes virtually all the landslide except that within and beneath the tip. In and beneath the tip the position of the slip surface is uncertain, though it passes through basalt fill and/or Chalk and Greensand material, and can be expected to have variable but relatively high strengths. Assuming that segment BB’C, considered separately, is on the point of movement (that is, the Factor of Safety for this por-
tion of the landslide, \( F=1.00 \), then the residual strength parameters are found to be \( c_r'=0 \), \( \phi_r'=14.0^\circ \). These parameters are consistent with the field residual strength reported by Chandler (1984) for other Lias landslides, and with the observation that is probably the portion of the slope that moved in the 19th century, and is therefore expected to be only marginally stable with a true Factor of Safety only slightly greater than 1.0.

The presence of fill on this portion of the landslide (Fig. 3), so long as its placement did not result in significant excess pore pressures, does not greatly influence the stability of this portion. This is to be expected since the angle of shearing resistance \( \phi_r' (=14^\circ) \) is numerically close to the inclination of the basal failure surface at the point where the fill is placed \((\approx 12^\circ)\); see Hutchinson (1984).

The Factor of Safety of this segment may well be a little different from the assumed value of 1.0, but whatever the true magnitude of \( F \) the results of subsequent analyses of different segments and loading situations can be expressed as Factors of Safety that will show if the situation being considered is more \((F>1.0)\) or less \((F<1.0)\) safe than segment BB'C.

In 1975 the tip crest on the line of section was at 89 m a.s.l. Assuming that the whole landslide at this time (Segment A'A'' A''' B' C) also had \( F=1.0 \), and that \( c_r'=0 \), \( \phi_r'=14.0^\circ \) for A' to C, where the shear surface is in Lias (or Lias derived) clay, the stability analysis shows that the mobilised strength parameters for A' to A'' are \( c_r'=0 \), \( \phi_r'=34.0^\circ \). This is a reasonable value for the combined strength of the basalt fill, and the Chalk and Greensand between A' and A''.

The effect of the addition of the further 9 m of fill to the crest of the tip between 1975 and 1977 can now be considered. Taking the values of \( c_r'=0 \), \( \phi_r'=34.0^\circ \) for the basalt fill, etc., and \( c_r'=0 \), \( \phi_r'=14^\circ \) for the Lias, as before, \( F \) falls from 1.0 to 0.92, an 8% reduction in the stability of the whole landslide. This is a significant reduction, and provides an obvious explanation for the recorded slope movements, and of the apparent acceleration in damage to the buildings reported from early in 1977.

5. Mechanics of the landslide

A notable result shown by inclinometers installed in boreholes C1 and C2 is that movement in each case occurred at two different levels. This is shown in Fig. 4, and can be seen in the line of section, Fig.3. Such an observation, while not unique, is certainly unusual.

With reactivated landslides, the majority of the observed movement generally occurs only at the basal sliding surface, the consequence of the landslide mechanism being well established by the original landslide movements. Movement does indeed occur on a single sliding surface in the lower (reactivated) portion of the landslide, recorded by the inclinometers in boreholes C3, C4 and C6.

That the portion of the landslide beneath the Works Tip (segment A'A''B') appeared to have been moving on two different shear surfaces suggests that a mechanism of potential collapse was in the process of developing, the consequence of the modified stress field applied by the weight of the tip. Since the Lias clay is a typical overconsolidated, stiff, plastic, and therefore brittle clay, this observation led to concern that the portion of the landslide directly beneath the tip might be suffering progressive failure, and that, with strain softening as the strength falls to residual, there might be an acceleration of the movement of the landslide.

These ideas may be examined by assigning strength parameters appropriate to first-time failures in Lias clay to segment A'A''A''' of the landslide, i.e. \( c'=0 \), \( \phi'=31^\circ \) (Chandler and Skempton 1974). If this is done for the 1975 tip height, then for a Factor of Safety of 1.00, a strength of \( c'=0 \), \( \phi'=31^\circ \) is mobilised on segment A'A'', a value that is a little lower than might be expected within the tip and Chalk/Greensand, but is not impossible. For the 1977 tip height, with \( \phi'=34^\circ \) for the tip and Greensand material, and \( c'=0 \), \( \phi'=23^\circ \) for the Lias on segment A'A''', the value of \( F \) becomes 0.99, or 0.92 if \( \phi'=31^\circ \) is used for the tip material.

The uncertainties of these analyses are such that clear conclusions cannot be drawn. However, movement was generated simultaneously on two different failure surfaces, which strongly suggests that a first-time failure and not a reactivated movement was occurring below the Works Tip. The analyses show that such a mechanism is certainly possible.

6. Remedial measures

The concerns that the landslide movement might accelerate led immediately to consideration of possible remedial works. Various measures were considered: in particular, drainage seemed a possible method, but the depth and extent of the drains required were considerable, and the time needed, both to complete the work and for drainage to become effective, was also of concern. Far more straightforward, particularly since
the necessary excavation equipment was immediately available, was to remove the crest of the Works Tip. This was done during February to October 1979, the crest height being lowered to 84 m a.s.l., involving the removal of 14 m of material, Fig. 3.

The effectiveness of the reduction of load on the landslide was monitored by inclinometers. By this time, the original inclinometers had been rendered inoperable by the landslide movement. Three further inclinometers were installed, at the locations of boreholes C1, C2 and C4 (Fig.3). The landslide movements indicated by these inclinometers are shown in Fig. 6. The dashed lines, which represent the periods of missing information when the inclinometers were inoperable, are estimates. The reduction in rates of movement from mid 1978 was probably the combined result of a small lowering of the piezometric level below the higher levels of the 1977-78 wet winter, combined with the development of a more stable configuration of the landslide as a result of downslope movement. It may be noted that an overall reduction of 0.5 m of the level of the piezometric surface in the landslide results in an increase of 2% in the Factor of Safety. It is also possible that passive resistance developed progressively in the downslope portion of the landslide, consistent with the diminishing downslope movements, thus aiding stabilisation.

The movement slowly reduced, eventually becoming stationary once the top of the Works Tip was removed. The corresponding Factor of Safety, with the lowering of the crest of the tip to 84 m a.s.l., was 1.03. Thereafter, there appear to have been no further movements of the Magheramorne landslide.

7. Conclusions
Considerable movements of a landslide at Magheramorne, Northern Ireland, occurred during 1977-78. Detailed investigations of this landslide, using both documentary sources and by means of boreholes and in-situ instrumentation, showed a number of factors of interest. The investigations showed that although a considerable portion of the landslide was the reactivation of an ancient coastal landslide, its movement was due to the construction of a tip of waste rock at the crest of the slope. Since this loading differed from that which caused the original landslide, the portion of the landslide at the crest of the slope beneath the tip appears to have been subjected to first-time shearing. Inclinometers down-slope from the tip showed that two separate shear surfaces developed, a relatively unusual observation, supporting the suggestion that this portion of the landslide was shearing for the first time. Had the movement been a reactivation, a single shear surface would have been anticipated.

The possibility that first-time shearing was occurring beneath the tip raised fears that there might be progressive failure of the ground in this region, and a consequent acceleration of the movement of the landslide. The most appropriate remedial solution to this problem was simply to remove the crest of the tip, and this was done during 1978. Stability analyses provide a quantitative assessment of the changing Factors of Safety (F) that reflect the landslide movement (with F computed to be <1.0), and then its stabilisation (with F >1.0). The considerable number of unknowns involved in the stability analyses are such that although the relative values of the Factors of Safety are a useful guide to the changing degrees of stability of the landslide, the absolute values should be regarded as indicative only.

The landslide showed minor evidence of movement (in 1973-75), with F≈1.0, moved at a greater rate (200 to 20 mm/year) after the tip height had been raised by nine metres (during 1975-77), with the corresponding value of F falling to 0.92. Removal of 14 m from the tip crest in 1979 increased F to 1.03, and was accompanied by a considerable deceleration of the movement to a near-stationary state. However, small movements (~10 mm/year) continued for at least a year, suggesting that passive resistance in the lower portion of the landslide built up slowly, gradually improving the overall stability of the landslide.

References