Quaternary anchialine karst development below present day sea level in Plymouth and its effect on foundation design

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Anchialine cave development occurs at the interface between saline and meteoric groundwater zones in a coastal karstic aquifer. This process has been described in detail for the submerged Blue Holes of the Bahamas, USA and is typified by the concentration of horizontal or shallow dipping solution cavities, which develop independent of structural geological controls. Concentrations of horizontal solution features associated with past sea level stands above 0 m OD have been described for the karstic middle Devonian Brixham Limestone Formation aquifer of Berry Head, Devon. Similar horizontal cavities occur in the coastal aquifer of the Devonian Plymouth Limestone Formation. Analysis of borehole information from three sites along the coastal edge of the Plymouth Limestone Formation indicates that concentrations of solution features can also be identified at various levels below the present day sea level. A number of these levels can be correlated with earlier sea level stands. Interpretation of the geotechnical behaviour of sediments infilling the solution features suggests rapid cave infilling in the last phase of marine transgression during the Holocene. The implications of solution voids on engineering design and construction are significant. Designing engineering solutions for foundations must consider anchialine void levels and characteristics and any change in surface water drainage can result in serious settlement and stability problems.

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Introduction

The presence of substantial solution voids within limestone poses a number of significant engineering problems (Waltham, 1989). The solution voids can reduce bearing capacity of the ground causing problems in designing building foundations. The erosion of superficial material into solution voids can result in settlement and are an important consideration in designing drainage. The irregular surface topography typical of limestone and the presence of pockets of superficial material can also cause problems with excavations.

The outcrop of the Devonian Plymouth Limestone Formation (undivided) stretches for nearly 10 km east to west and is up to 1 km wide (Figure 1). Its substantial western limit is the River Tamar, where it is truncated by the Cambeak Fault Zone. The eastern edge of the limestone is truncated between thrust units of Middle and Upper Devonian slaty mudstones. Much of the southern boundary is submerged beneath Plymouth Sound, where it is deeply incised by the lower reaches of the drowned valleys of the rivers Tamar and Plym. The sides of these valleys, where they cross the limestone outcrop, are steep-sided. The more elevated sections of these valleys above present day sea level, form the foreshores of Plymouth Hoe, Cattedown, Turnchapel and Oreston. By the early 19th Century, much of the original topography of the valley slopes in the latter three areas had been destroyed by large scale quarrying. Only along the historical Plymouth Hoe foreshore does anything like the original topography remain where the ground rises as a craggy series of cliffs to the prominent promenade level of 35 m OD.

Below sea level there are a number of submerged resurgences (springs) on the valley sides. The largest of these is known as the Millbay Blue Hole, which emerges at the base level of the incised river valleys at -35 m OD.

The Plymouth Limestone Formation is structurally complex (British Geological Survey, 2002) comprising a thrust duplex, modified by secondary thrusting. The formation was later affected by steep extensional strike faults and cross cutting strike-slip faults. The limestone forms part of the Plymouth High Succession, which is now represented in two relatively thin thrust slices. The lower thrust sheet overrides the slates of the Upper Devonian Saltash Formation to the north. The junction between the limestone and the slates has been exposed during previous construction works in Union Street, Plymouth (grid reference: SX 467 545) and indicates that the contact is at a very low angle. When seen in the temporary exposures in Union Street the overlying limestone sheet was fragmented into a broken blocky mass for a thickness of approximately 5 m above the slate.

The higher thrust zone, which occurs within the limestone outcrop, can be seen exposed in Chelson (SX 518 546), Moorcroft (SX 527 540) and Sherford (SX 546 538) quarries that have been excavated in the eastern end of the limestone outcrop. It has been argued that this second thrust zone acts as an effective aquiclude between the two limestone sheets and that separate water flow regimes occur within these two sheets (Roxburgh, 1987). However, dye tracing analysis between the eastern end of the upper sheet and the Millbay Blue Hole resurgence, located in the western half of the lower sheet, would indicate that there is at least, significant, localised hydrological continuity between the two limestones.

Anchialine cave development has been described as a major mode of cave development for the Bahaman Blue Hole cave systems (Palmer and Williams, 1984; Palmer *et al.*, 1986). Such caves form at the junction between the fresh and salt-water

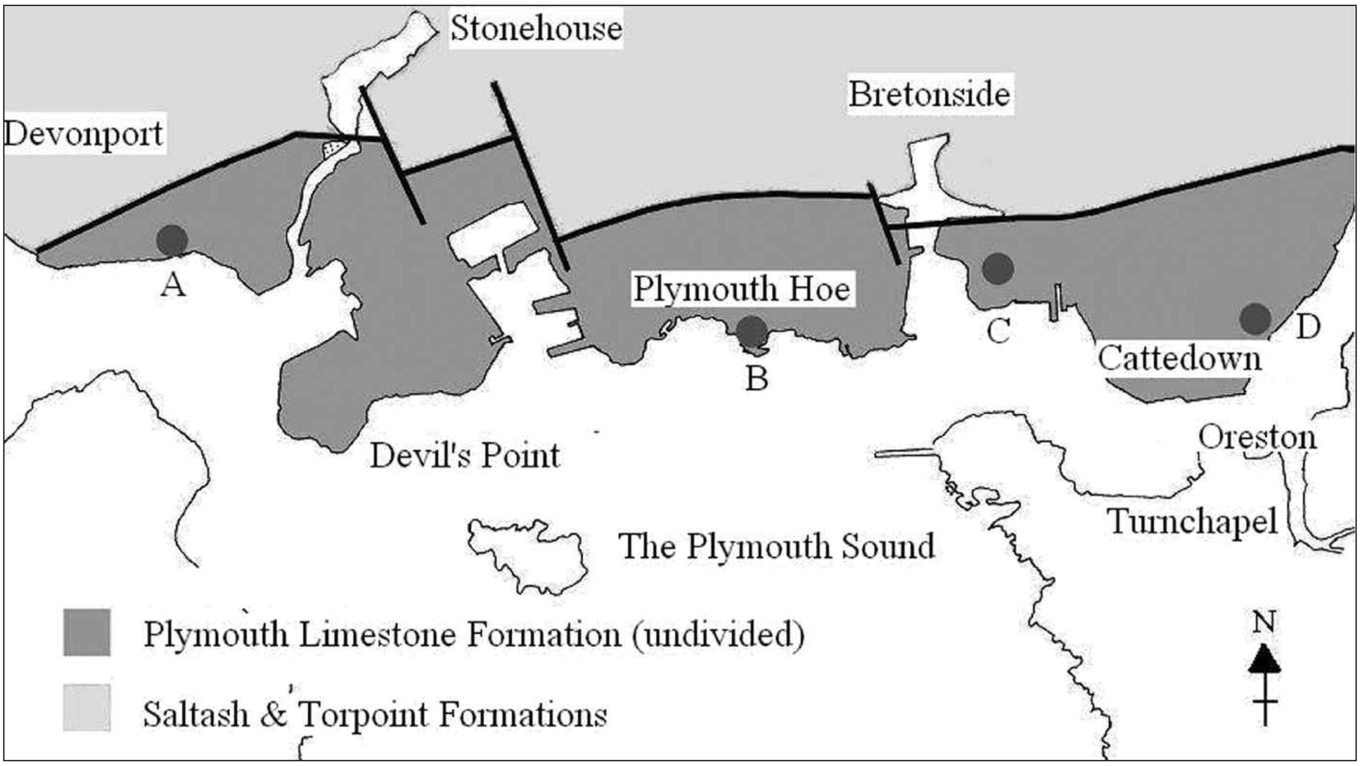

Figure 1. *Sketch map showing the outcrop of middle Devonian Plymouth Limestone Formation in Plymouth. Sites A to D are referenced within this paper.*

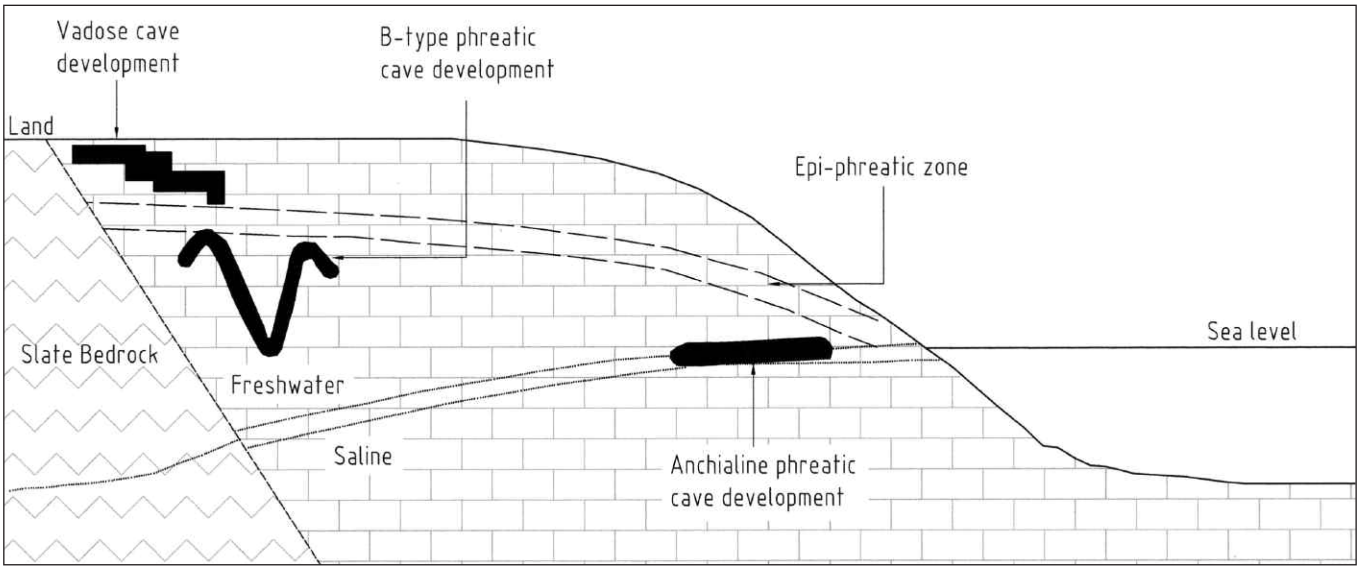

Figure 2. *Schematic diagram showing types of cave system development in limestone.*

interface that forms within the body of groundwater adjacent to a coastal outcrop (Figure 2). Where still stands occur within a changing sea level curve, these still stands can be preserved as a series of roughly horizontal cave passages a few metres below the still stand level. Such a record of sea level changes above the present day sea level have been identified from cave elevation analysis of the Berry Head Caves in the South Devon area (Proctor, 1988) and can be seen in several locations along the Plymouth foreshore (at approximately 1.5 m below the level of the 8.5 m OD raised beach), as well as in a number of large quarries (Figure 3). The findings of several borehole investigations along the foreshore of the Plymouth Limestone Formation suggests an extension of the record for cave development below the present day sea level from 0 m OD to -18 m OD.

Site investigations

Data for this analysis has been obtained from borehole investigations carried out at three sites along the coastal limestone margin in Plymouth. Two engineering investigations (referred to as sites A and B), approximately 2 km apart, were carried out for Plymouth City Council. A further site to the east (referred to as C) extends the lateral distance between observations by a further 1.5 km. The approximate locations of sites A, B and C are shown in Figure 1, as is site D (the quarry shown in Figure 3).

Data from a total of 17 boreholes extending to a maximum depth of -28 m OD were used in the analysis. All boreholes were drilled using DTHH (down-the-hole-hammer) technique. All boreholes were supervised and logged by a qualified

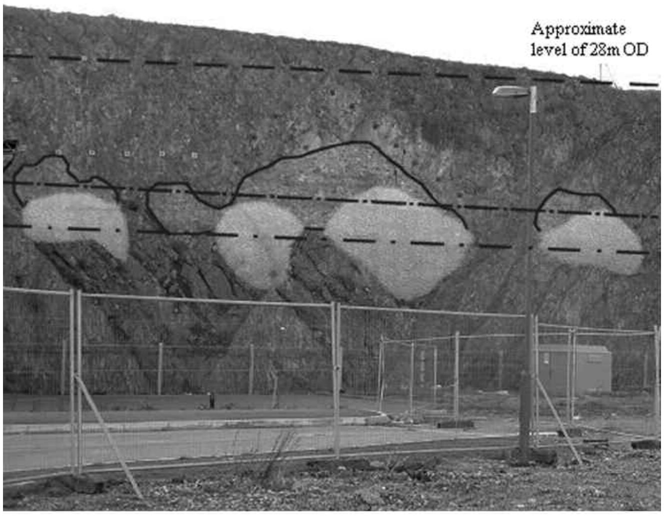

Figure 3. *Quarry face (Site D) showing two phases (the lower phase filled in grey; upper phase outlined) of near-horizontal phreatic cave development. The dashed-dotted lines are approximate sea level stands related to each phase of cave development.*

engineering geologist, enabling a good record of changes in drill penetration, drill returns, ease of drilling and other relevant observations.

In addition to borehole logs, a number of Lugeon Test results were used to provide an interpretation of the engineering properties of encountered void infill. The Lugeon Test is a standard engineering site investigation test and entails sealing a portion of the borehole with hydraulic inflatable packers and then measuring the flow of water that can be achieved into the rock across the sealed zone under differing hydraulic heads (Clayton *et al.*, 1982). The changing flow behaviour under differing heads was used to interpret properties of fissure infill.

Void analysis

The analysis attempted to correlate the frequency of voids encountered in the boreholes with published sea level stands for the late Pleistocene. It involved tallying all voids encountered in 1 m intervals in the complete set of boreholes. These tallies were expressed as a percentage of the total number of boreholes and weighted according to a ratio of the number of drilled boreholes that extended to depth, to the total number of boreholes drilled (Table 1). Before weighting moderate peaks were evident; weighting enhanced these peaks when charted (Figure 4). Allowance was also made for vertical voiding; i.e. only the level of their first occurrence within the borehole length was taken into account. The consistent quality of borehole logging has also allowed the voids to be ascribed as filled or open.

In Figure 4 it is evident that there appear to be two sets of double peaks between -2 to -8 m OD (labelled E1 and E2) and -12 to -16 m OD (labelled D1 and D2). These two sets of peaks show good correlation with predicted anchialine void development related to two published sea level stands at -1 m and -8.5 to -9 m OD (Cullingford, 1985). It suggests that anchialine void development occurs between 3 m and 6 m below the level of the sea level stand. A similar double peaked nature is indicated by Proctor (1988) for curves of volumetric cave development against cave altitude observed for the Berry Head limestone for the +3 and +8.5 m OD sea level stands. Significant similarities in void types for the E1, D1 and E2, D2 peaks are demonstrated in Table 2, indicating a cyclic nature to development.

E1 and D1 voids were possibly developed during periods of slightly more elevated sea levels than the associated E2 and D2 peaks. Wilson and McKenna (1996) recorded a similar relatively

Depth (mAOD)	No. of voids	No. of BHs penetrating interval	% voids	Significance weighting	Weighted % voids
3	0	12	0	0.71	0
2	0	12	0	0.71	0
1	0	13	0	0.76	0
0	0	15	0	0.88	0
-1	0	17	0	1.00	0
-2	3	17	6	1.00	6
-3	3	17	18	1.00	18
-4	3	17	18	1.00	18
-5	2	17	12	1.00	12
-6	4	17	24	1.00	24
-7	1	17	6	1.00	6
-8	0	17	0	1.00	0
-9	0	17	0	1.00	0
-10	3	17	18	1.00	18
-11	1	17	6	1.00	6
-12	4	17	24	1.00	24
-13	6	17	35	0.82	35
-14	4	17	24	0.65	24
-15	2	14	14	0.65	12
-16	2	11	18	0.47	12
-17	1	11	9	0.35	6
-18	1	8	13	0.35	6
-19	0	6	0	0.29	0
-20	1	6	17	0.29	6
-21	1	5	20	0.29	6
-22	0	5	0	0.29	0
-23	0	5	0	0.29	0
-24	0	5	0	0.29	0
-25	1	3	33	0.18	6
-26	0	3	0	0.18	0
-27	0	3	0	0.18	0
-28	0	1	0	0.06	0

Table 1. *Statistical analysis of voiding. Significance weighting was based on the ratio of the number of boreholes drilled that extended to depth, to the total number of boreholes drilled.*

short period rise at 6,500 years BP in the Bann Estuary, Northern Ireland, which was followed by a fall of approximately 3 m. The evidence from anchialine cave development in South Devon would suggest that similar pulses of short-term sea level rise occurred with the preceding two Ipswichian sea level stands. Massey *et al.* (2008) indicate a significant reduction in the rate of sea level rise at approximately 7000 yr BP commensurate with a sea level of – 8.5 m OD.

The presence of the two distinct sub-peaks could also possibly be due to changes in aquifer recharge during the sea level stand (i.e. a variation in the piesometric level in the aquifer altered the level of the zone of freshwater saltwater mixing).

It is considered that the higher void zone (Peak E1) may also comprise a component of voids that may have developed during the Ipswichian Interglacial period. However, Proctor (1988) suggests peaks associated with this period occur at +2.5 m OD and 0 m OD. Figure 5 is a compilation of void occurrence for the altitude range -28 m to +30 m OD from both

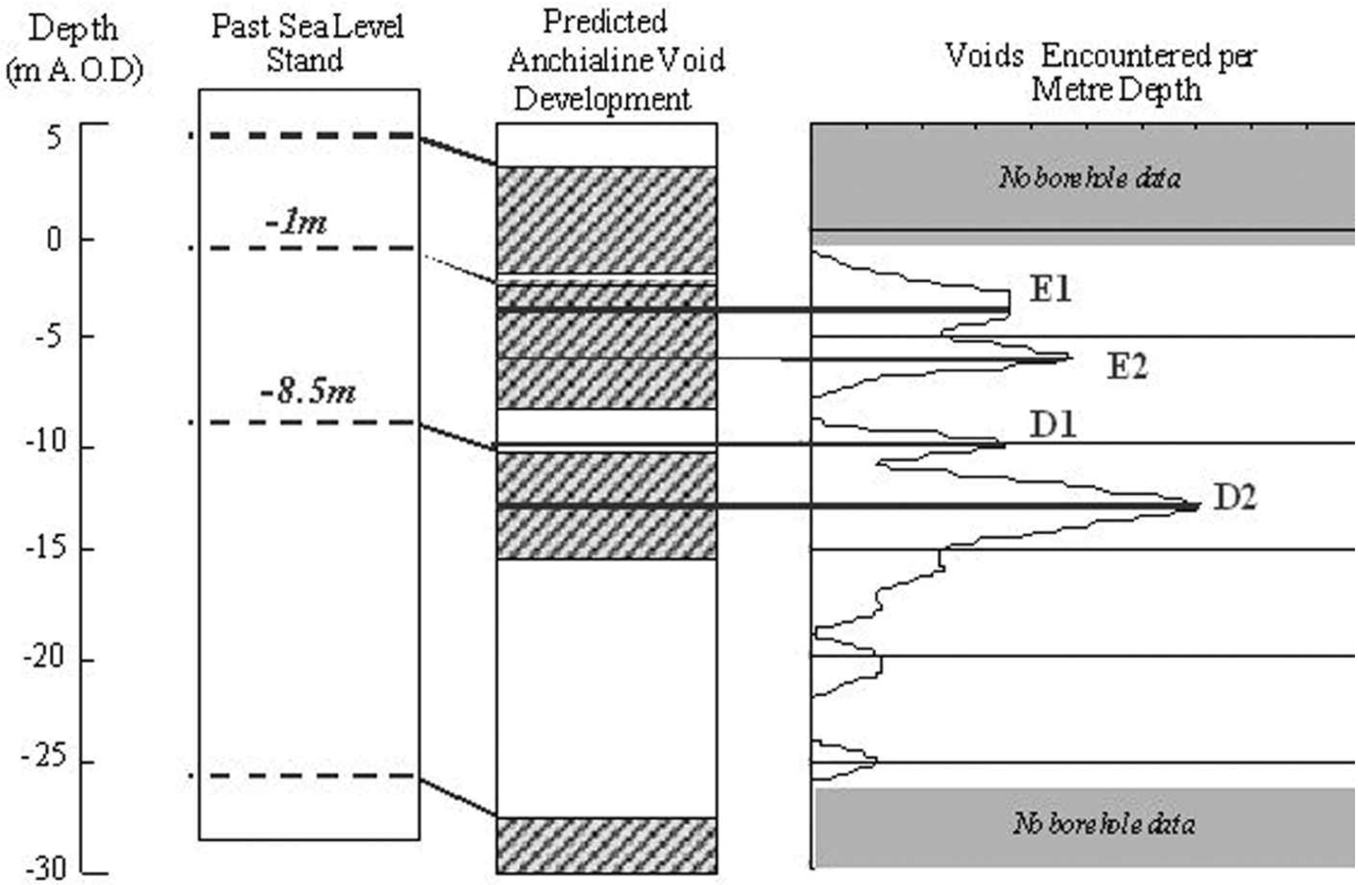

Figure 4. *Void correlation against past sea level stands. The two peaks of void development correlate with past sea level stands, with the major void concentration (2nd peak) being approximately 3 m below the sea level stand.*

Void peak	**Open**	**Infilled**	**Horizontal**	**Vertical**	**Void genesis**	**Infilling phases**
E1	1	3	4	0	Anchialine	Sea level fall E1 – E2
E2	4	0	3	1	Anchialine, some vertical mixing	
D1	0	2	2	0	Anchialine	Sea level fall D1 – D2
D2	2	3	3	2	Anchialine, some vertical mixing	Sea level rise D2 – E1
below D2	3	0	0	3	Phreatic rifting during downcutting	

Table 2. *Analysis of void type indicates similarities in for the E1, D1 and E2, D2 peaks, which suggests a cyclic nature to development.*

Proctor (1988) and site investigations conducted by John Grimes Partnership. None of the boreholes drilled in these investigations encountered predicted voids related to the sea level stand of -26.5 m OD.

Lugeon tests were carried out using seawater across an infilled void associated with Peak D2 (Figure 6). Below the packer, the borehole comprised solid rock except for a short infilled void section at around -15 m OD. Pressure and flow were recorded at the pump outlet. The results of the test (Figure 6) indicated that there was a sudden increase in flow rate at an excess head of 8.5 m. This can be ascribed to mobilisation of void infill resulting in a slight increase in permeability. After this initial flow breakthrough, a linear decrease in flow occurred with reduction in head. Head was reduced to a minimum level that could be maintained by the pump after which the flow ceased. After five minutes, a second cycle of pumping was resumed. Flow breakthrough did not occur until the initial head of 8.5 m was again obtained, at which a sudden increase in flow occurred. There was no reduction in infill permeability during the two cycles. This behaviour would indicate that the fill was highly thixotropic in nature. Previous experience with introducing seawater into freshwater laid cave deposits infilling at Cattewater, Plymouth, resulted in a rapid and dramatic reduction in infill permeability. No such reduction was observed in the results from the cyclic Lugeon tests, suggesting that the infill was laid down in saltwater, which would be consistent with Middle to Late Holocene age deposits. The findings would suggest that rising sea levels resulted in more deposition of river derived silt and other sediments within the lower sections of the Plym and Tamar rivers (Eddies and Reynolds, 1988).

At Site B, boreholes were spaced over a sufficient distance away from the foreshore for a tentative distribution of the E peak voiding to be observed. At this location, it would appear that the E peak voids extend inland of the present foreshore to a maximum of 160 m. Other investigations further inland within the Plymouth Limestone Formation have failed to determine any significant increase in void occurrence at the level predicted for the E peak voids.

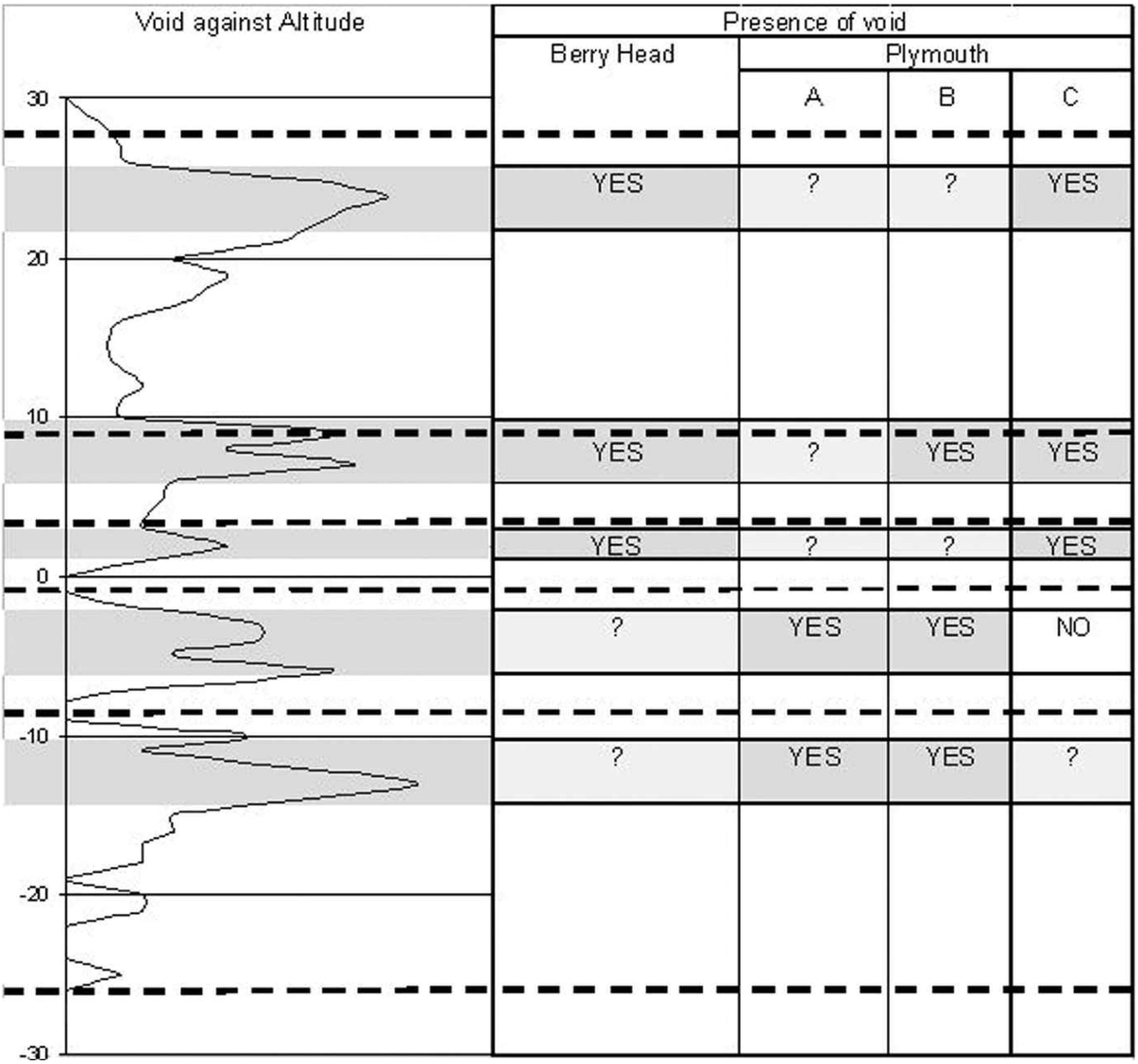

Figure 5. *Correlation of anchialine cave development levels in coastal aquifers in the South West of England.*

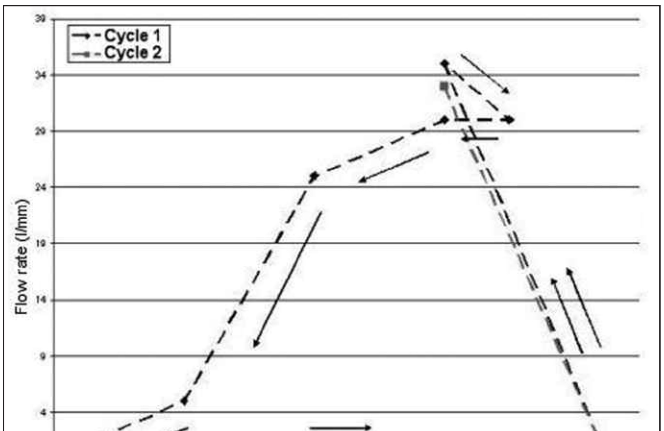

Figure 6. *Lugeon test results on D2 Peak. Flow breakthrough occurred at a head of 8.5 m in both cycles indicating that the void infill was highly thixotropic in nature.*

Conclusions of void analysis

Altitudinal analysis of cave void occurrence indicates that for published sea level stands, two sub-peaks can be identified in the cave record. It is proposed that these sub-peaks represent either short periods of sea level rise followed by a fall to a longer period of constant sea level, or record a sharp change in aquifer recharge during the period of the sea level stand. Sediments preserved within voids below current sea level would appear to reflect changes in sediment flux during the Holocene. They also indicate that major sediment build up occurred during sea level rise between peaks and sediment deposition occurred between sub-peaks.

Major concentrations of voids have been found to occur at approximately 3 m below the published sea level stands of -1 m and -8.5 m OD. A record of pre-Ipswichian (oxygen isotope stage 7) through to the late Holocene sea level rise is preserved within the coastal cave systems of South Devon (Proctor and Smart, 1991). Changes in sea level over this period range from -16 m OD to +28 m OD. Uranium series dating of stalagmites buried in the sediment indicates the earliest dated deposits (oxygen isotope stage 7) occur as a marine transgressive sediment (Note: the age for the sediment is a maximum, whilst the stalagmite age gives a minimum age for the void. However, Proctor and Smart (1991) do not rule out that the cave development may record a sea level event significantly older than the dated stalagmite).

Interaction of allogenic and anchialine elements in a karst block

Allogenic karst development occurs in a limestone block where a significant stream input is present. This results in the development of sinkholes, stream caves and resurgences with a general concentration of drainage towards a few master conduits and springs. These are known as B-type cave development (Jakucs, 1977). A further feature of this type of development is the presence of plunging and rising phreatic passages known as loops.

At Site C, the presence of both anchialine and an abandoned, sediment infilled B-type, phreatic loop were present over different sections of the site. Areas underlain by anchialine features were separated from areas where phreatic cavities were present by conspicuous faulting. The fault blocks appear to provide a control for different hydrologic conditions. Figure 7 presents a schematic diagram of the general situation on Site C. It is possible that the presence of the phreatic system within some blocks increased the ability for freshwater to circulate, potentially depressing the zone of freshwater and saltwater mixing.

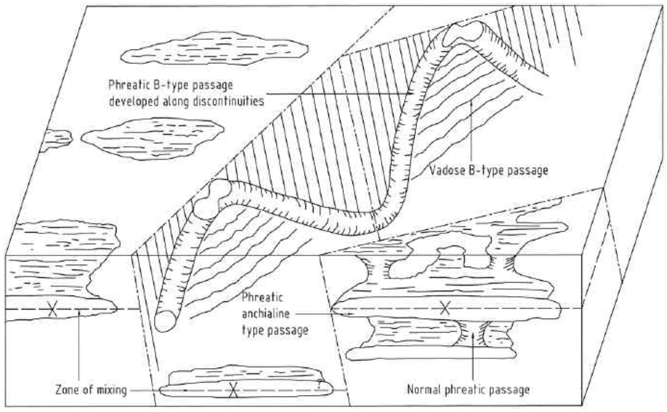

Figure 7. *Schematic model showing the juxtaposition of anchialine and B type phreatic karst development in the Plymouth Limestone Formation.*

Construction implications

Construction over areas of limestone is problematic for both surface water drainage and foundation considerations (Waltham, 1989). Either decreasing or increasing surface water drainage can result in serious settlement and stability problems, while designing engineering solutions for foundations must consider anchialine void levels and characteristics.

Changes in land-use where surface water drainage will be drastically reduced, such as hard impermeable surfacing, could give rise to a significant reduction in the moisture content of any clayey infill within the vadose (percolation zone) level. Any such reduction could give rise to shrinkage in the clay and consequent loss of support to potentially unstable voided bedrock features. Surface soakaways are generally inappropriate, as any discharge with concentrated water flow at high levels into infilled cavities can lead to erosion of the infill material and consequent surface subsidence. Whilst it may be possible to dispose of surface water into the ground, such discharges should be carefully designed such that existing ground conditions are preserved and potential for erosion of fissure infill avoided.

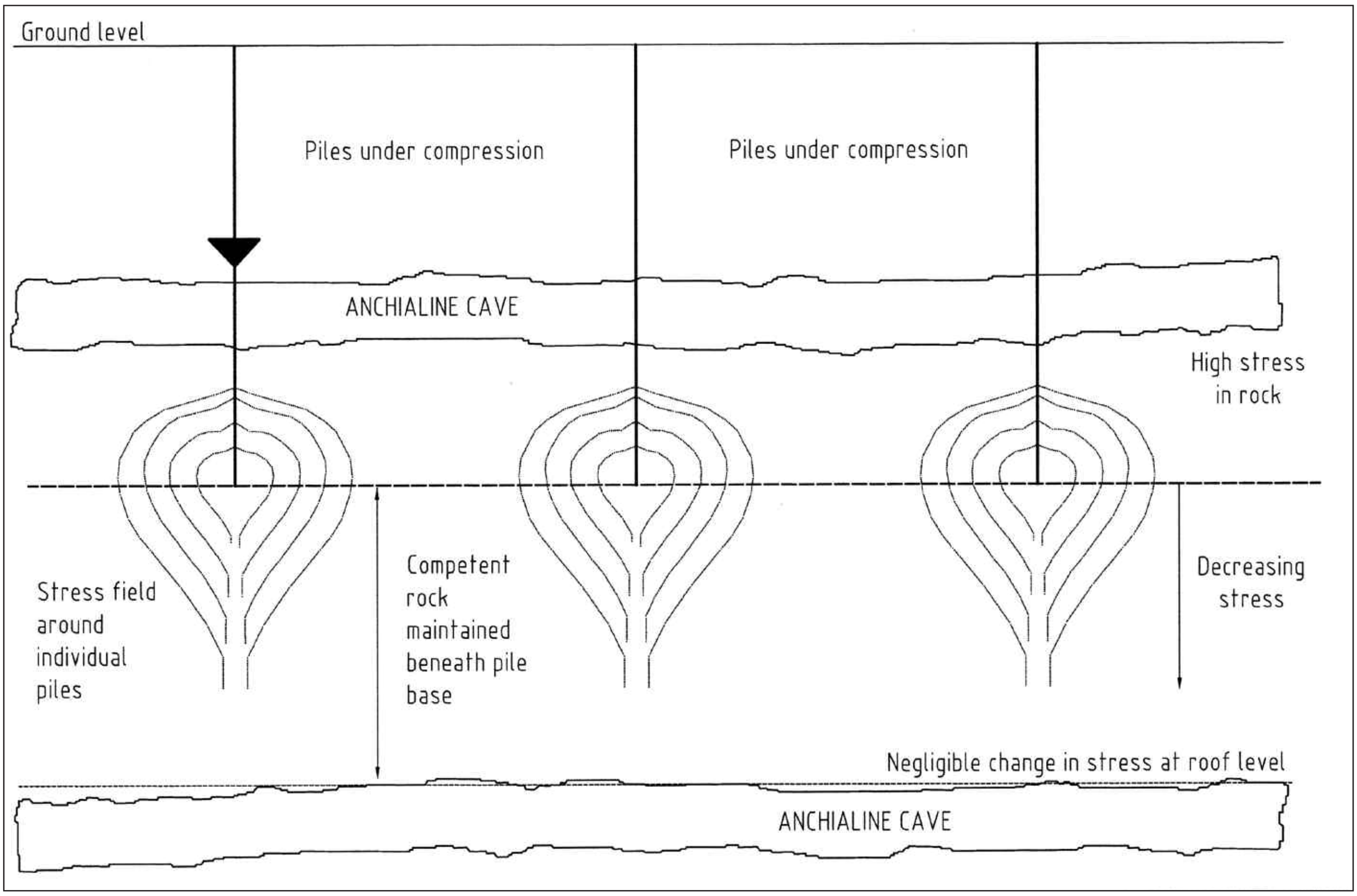

Figure 8. *Diagram showing optimum pile socket positions.*

Ground bearing foundations are considered to be inappropriate where E peak voids occur at shallow depths. Due to the horizontal nature and implied aquifer function of the voids, grouting is not recommended as a ground improvement option. Piles designed on skin friction only are considered the best method for transference of structural loads. Piles should be socketed into competent rock, with sufficient thickness of rock maintained beneath the base of the pile and the next level of predicted anchialine void development. This will allow for decreasing stress levels below the pile base to represent a negligible change in stress at roof level of the underlying voids (Figure 8).

Tension piles should be designed so that cones of pullout overlap to provide sufficient resistance to the tensile pile force within the rock mass without requiring transfer of load across any void zone (Figure 9). In highly loaded piles, fibre reinforcement could be used to provide tensile capacity in the pile concrete to resist bursting forces.

As the infilling of voids is variable, permanent casing or similar should be used to ensure concrete is contained within the pile circumference above the socket length. Where piles are designed to work in tension, special consideration of extension should be made to ensure concrete cracking does not occur due to the marine environment.

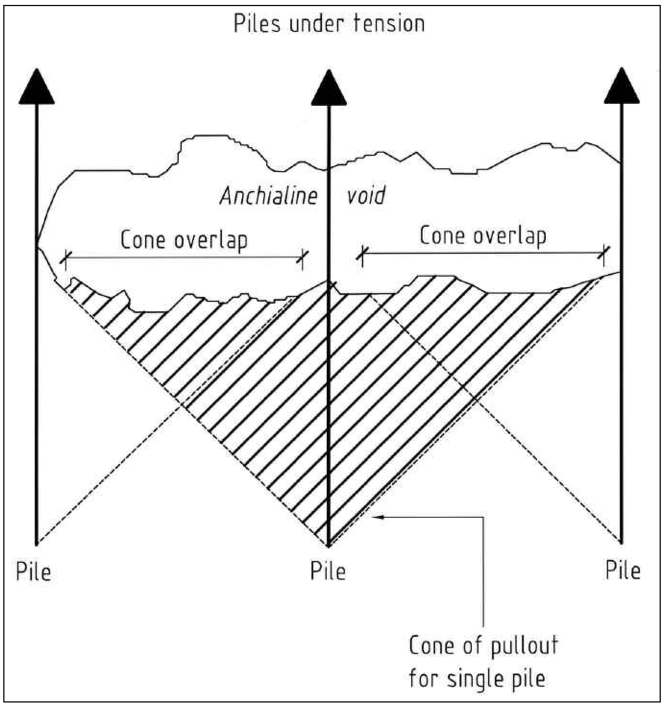

Figure 9. *Conceptual diagram showing recommended overlap for piles.*

Discussion

Site investigations at a number of locations along the coastal edge of the Plymouth Limestone Formation have provided evidence for the existence of submerged anchialine type caves. These are concentrated at levels of -2 to -8 m OD and -12 to -16 m OD. These voids appear to be related to major published sea level still stands at -1 m and -8.5 m OD. The -8.5 m OD level correlates with the sea level at approximately 7000 yr BP when the rate of sea level rise reduced significantly in South West England.

Morphogenetic models have been proposed for two construction sites. Implications for construction include: (a) that where piled foundations are recommended their design should be based on skin friction and (b) traditional soakaways are inappropriate as changes in surface water drainage can result in serious settlement and stability problems.

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