The Institution of Structural Engineers

Possible solution to past CM examination question

Question 1 - April 2009

Office building incorporating an existing stone tower

by Dr Peter Gardner

The information provided should be seen as an interpretation of the brief and a possible solution to a past question offered by an experienced engineer with knowledge of the examiners’ expectations (i.e. it's an individual's interpretation of the brief leading to one of a number of possible solutions rather than the definitive "correct" or "model" answer).

Question 1. Office Building Incorporating An Existing Stone Tower

Client's requirements

1. An existing stone tower is to be used in a new office development; see Figure Q1.
2. The tower is made from stone set in mortar and cannot be used to support the new office structure in any form. The new building is to be set partially into the interior of the tower as shown on Figure Q1.
3. The Architect wishes to retain the smallest floor depth possible and to have the building clad entirely in glass. The Architect has also stipulated that there is to be no visible structure around the glazed perimeter other than columns and the floor plate. Columns are to be spaced at least 8.0m apart.
4. The building is to have a 3.1m clear height between each floor and ceiling and is to be 4 storeys high. The height of the tower is 16.5m. The Architect has requested that the maximum level of the roof line of the building matches the height of the tower.
5. The existing stone tower is founded at a constant depth of 1.0m below ground level. The foundation of the tower does not extend beyond its plan area.

Imposed loading

6. Roof 2.5kN/m^2
   Floor loading 6.0kN/m^2
   Loadings include an allowance for partitions, finishes, services and ceilings.

Site conditions

7. The site is level and located in a park in the centre of a town.
   Basic wind speed is 40m/s based on a 3 second gust; the equivalent mean hourly wind speed is 20m/s.
8. Ground conditions – Assumed to vary linearly between boreholes

Borehole 1	Ground – 1.0m	Made ground
	Below 1.0m	Rock. Allowable bearing pressure = 1000kN/m^2
Borehole 2	Ground – 5.0m	Made ground
	5.0m - 8.0m	Stiff clay C = 80kN/m^2
	Below 10.0m	Rock. Allowable bearing pressure = 1000kN/m^2

Omit from consideration

9. Detailed design of staircases

SECTION 1 (50 marks)

a. Prepare a design appraisal with appropriate sketches indicating two distinct and viable solutions for the proposed structure. Indicate clearly the functional framing, load transfer and stability aspects of each scheme. Identify the solution you recommend, giving reasons for your choice. **(40 marks)**

b. After the design has been completed, the Client advises you that he wishes to include an atrium opening of the full width of the building at the south end with the floors set back by 5.0m from the south wall. Write a letter to the Client explaining how this might be achieved. **(10 marks)**

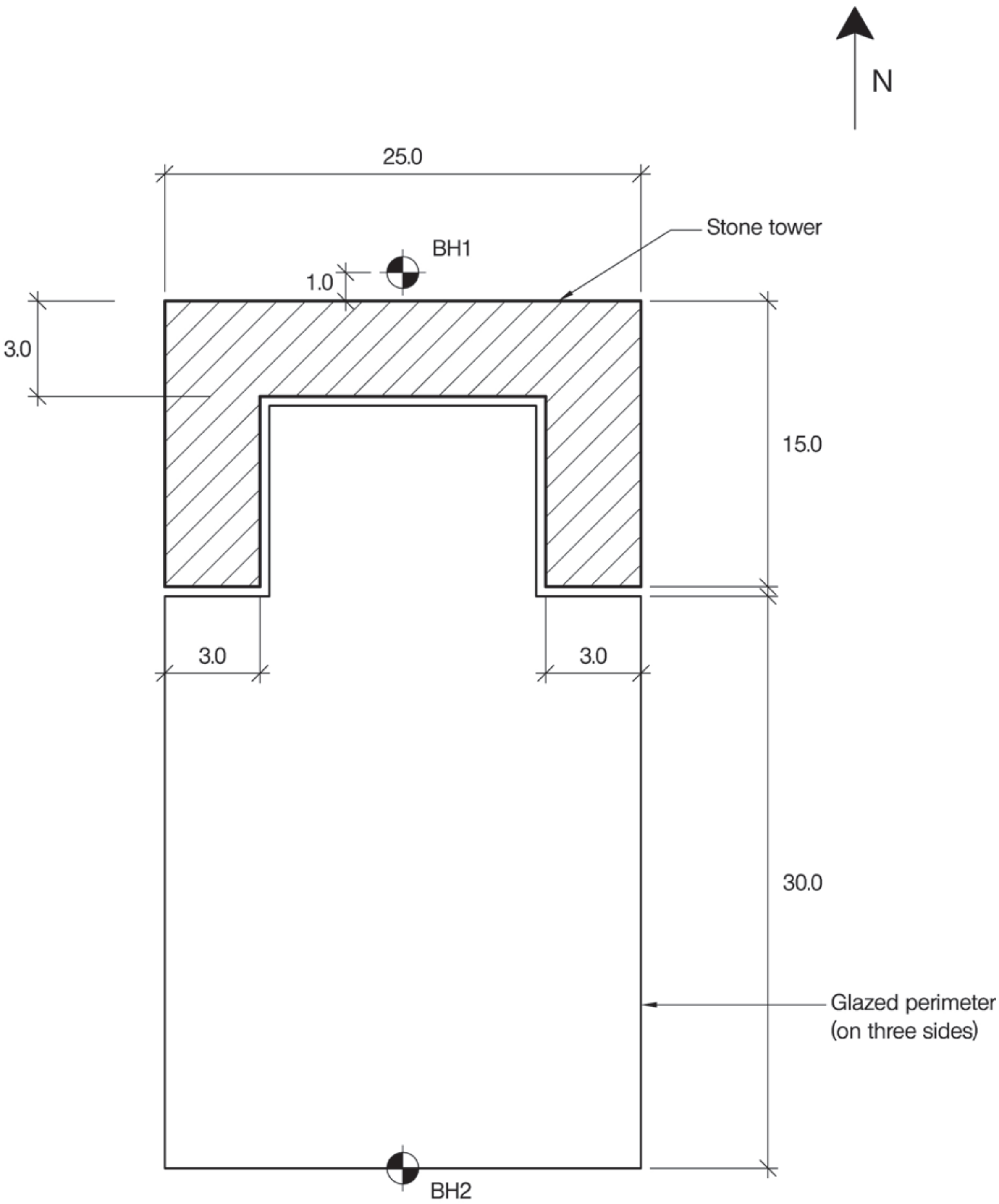
SECTION 2 (50 marks)

For the solution recommended in Section 1(a):

c. Prepare sufficient design calculations to establish the form and size of all the principal structural elements including the foundations. **(20 marks)**

d. Prepare general arrangement plans, sections and elevations to show the dimensions, layout and disposition of the structural elements and critical details for estimating purposes. **(20 marks)**

e. Prepare a detailed method statement for the safe construction of the office building and an outline construction programme. **(10 marks)**



PLAN

NOTE: All dimensions are in metres

FIGURE Q1

Introduction

This question relates to a new office development wrapped around an existing stone tower. The new office building is structurally independent from the tower, but is clearly intended to be architecturally linked. There are structural implications to consider.

The brief is relatively straightforward with clear constraints. The building is of comparatively modest scale, so first impressions are of an understandable question without any insurmountable difficulties.

The issues

- The brief states that the tower cannot be used to support the new office and that the foundations of the tower do not extend beyond its plan area. Any attempt to use the tower for structural support would result in automatic failure.

- There is a client requirement for slender floors and for the building to be clad entirely in glass. There is a stipulation of no visible structure around the glazed perimeter other than the columns and floor. This means there can be no diagonals, or any other form of additional structure around the perimeter. The key requirement is for "no visible [additional] structure around the glazed perimeter" so strictly speaking additional structural elements could be added anywhere as long as they are not actually on the perimeter, but the spirit of this requirement is surely to provide clean uncluttered lines when viewed from the outside. However, in a fully glazed building any internal structural elements would be visible, wherever placed!

- Columns are to be spaced at least 8 metres apart. There is no specific reference to external or internal columns, so this should be read to be all columns. The examiners are rightly hard on any candidate who infringes any of the stipulated client requirements.

- The building is to have a 3.1 metre clear height between each floor and ceiling, and the overall height of the building must not exceed that of the tower. So effectively this constraint sets the maximum floor depth. Even at this stage, without the benefit of any calculation, you should be preparing yourself to design/specify relatively slender floors spanning at least eight metres.

- The ground conditions are clear, with two borehole logs showing varying depths of made ground, stiff clay and rock. The question says that you may assume the ground conditions vary linearly between boreholes, and the existing stone tower foundations are one metre below ground level, so actually the stone tower sits on the made ground or stiff clay on all but its northern edge. This is somewhat curious and is unlikely to be the case in practice, however the question is about a new office building and not about the stone tower, so there is no reason for us to concern ourselves about the foundations of the stone tower, other than to make sure the new building doesn't interfere with them. Despite the borehole profiles, it might be reasonable to assume that the tower is founded on rock, in which case the new building will not influence the foundations at all, however as discussed above, a literal interpretation of the data suggests that the tower is on rock on its north face and on softer ground on the southern end. By ensuring that the foundations of the new building are kept away from the tower, the more onerous of the two interpretations relating to the tower's foundations can be easily dealt with.

In summary, the critical elements that will impact on the overall design appraisal and resulting schemes are: the floor depths, the column spacings, requirement for structural independence from the tower (superstructure and foundations), the stipulation of no visible structure other than the columns and floor around the perimeter, the stability system and dealing with the variable soil conditions.

Proposed solution

Bearing in mind that all the way through any of these questions you need to have firmly planted in your mind the need to provide two distinct and viable solutions, the obvious starting point would be to quantify the constraints: initially the available construction depths and then the column layouts.

Floor depths

The brief says “the architect wishes to retain the smallest floor depth possible”. A simple calculation (see figure one) shows that there is in fact ample floor depth. This leaves a choice, either to have a building overall height less than the tower (the question says “maximum level of the top of the tower”, not that it must be the same height) or have a floor depth greater than the absolute minimum. Because the question specifically states “smallest possible floor depth”, my advice would be to demonstrate your ability to design slender floors. One way of squaring this circle would be to design a minimum depth floor and use the resulting available space for services (raised floors and/or ceiling voids) with a commentary saying that the overall height could be reduced by allowing less service space.

Column layout

The next step is probably to lay out the columns, providing as much variation as possible within the absolute constraint of a minimum centre to centre spacing of 8 metres. There is no reason why columns shouldn't be adjacent to the stone tower, but we must bear in mind that the foundations to these columns may need to be set back to avoid surcharging or disturbing the material under the stone tower. Figure 3 provides four possible layouts.

A more radical column layout (longer spans and cantilevered floors) would provide greater variation between the schemes but this would immediately conflict with the minimum floor depth requirement.

Stability system

The next area to consider is probably the stability system which often provides opportunities for variation for the two required schemes. In this case we are prohibited from having any form of additional stability system in the glass clad elevations. It is less clear whether bracing is allowed on the new building/stone tower interface. We therefore need to think about the constraints in relation to the interface between the stone tower and the new building. The brief says "the building is clad entirely in glass" but the diagram clearly says the glazed perimeter is on three sides. This leaves the detail of the interface between the stone tower and the new building open to interpretation, which in turn has implications for the stability system. There are three possible interpretations/assumptions, the first is that the glazed perimeter continues around the stone tower, the second is that solid cladding (eg brickwork) is used, and a third is that the elevations are open, allowing the face of the stone tower to form the internal walls, with a weatherproof (but not structural) joint between the two. Each of these assumptions provides different constraints on the stability system: the assumption of a solid wall enables the use of shear walls, whereas the visually open assumption would limit the use of these elevations to aid stability (see figure 4).

The building must clearly have some form of vertical access in the form of stairs (and possibly a lift) which would be enclosed in a fireproof shaft. It would seem reasonable that these somehow could be used to contribute to the building's stability, either as a shear core or to locate diagonal bracing. At this point we need to consider how shear cores would fit in with the requirement for columns to be spaced eight metres apart: are they to be fitted around the columns, are they allowed in addition to the columns and how close to the perimeter can they go? Whatever you decide, the cores must be kept away from the perimeter (at least on the three exposed sides).

Whatever is proposed, the arrangement must be symmetrical so as not to induce torsion in the overall structure. Some candidates (possibly as a consequence of their interpretation of the brief) offered stability systems (cores and/or bracing) concentrated at the north end adjacent to the stone tower. This would induce significant torsion, which was ignored (this was a significant error!). A symmetrical system at the north and south ends completely overcomes this problem.

The above discussion is leading us to provide a stability system comprising internal shear walls and/or vertical bracing and an alternative with no additional internal structural components, relying on the frame to provide lateral resistance.

The option of a full moment-frame in both directions would provide a visually uncluttered building and crucially a distinct and viable alternative to a braced frame. The main discussion point with this option is the increased flexibility of the frame which will result in increased lateral movement, which is especially important adjacent to the stone tower (this was not appreciated by many candidates who attempted this question).

Ground conditions and foundations

As far as the ground conditions are concerned, we have rock relatively close to the surface at the northern end and a deep seam of made ground, with a further three metres of stiff clay on top of rock at the southern end (see figure 2). Although it would be theoretically possible to found the building on the stiff clay, there is a very significant issue of differential settlement. Also, from a practical point view the stiff clay starts five metres down, at the southern end, which would be deep (but feasible) for the construction of traditional foundations. By going down an extra three metres the whole building can be founded on the rock, which seems the only practical solution.

By founding the new building on the rock, its foundations cannot surcharge any soft ground under the stone tower. To avoid any disturbance to the existing structure the new foundations should be positioned away from the tower's footings (this may necessitate cantilevered foundations or ground beams if the columns are located on the perimeter). However, even though this isn't strictly in accordance with the data given, it would seem reasonable to assume that the tower is on the rock. In these situations a discussion of the various options/interpretations resulting in an argued assumption (as I have done here), seems a reasonable approach.

A combination of different column layouts, different stability systems, possibly combined with variations in the foundation system, would therefore form the basis of our "two distinct and viable schemes".

Letter

In this particular question the letter gives tremendous opportunity for discussing the structural implications of various options that can be proposed to meet clients revisions.

The client wishes to introduce an atrium at the south end the building with all the floors set back five metres from the south elevation. This will have a fairly dramatic effect on the whole structure and gives a perfect vehicle for discussion in the letter.

The inclusion of an atrium is likely to interfere with the framing arrangements and the stability system. Because the building has been based on a minimum clear column spacing of 8 metres, the atrium will compromise the symmetry of the overall grid layout. The "obvious" grid layout is a line of internal columns 5m from the south elevation with the remaining columns evenly spaced (on a 9.25m grid) but this clearly infringes the original brief. Adherence to the existing 8m minimum spacing will necessitate a 3m cantilever with all the inherent disadvantages (deflection/vibration). The letter can therefore discuss the possibilities afforded by a modification of the eight metre requirement, and the alternatives if the constraint stays. Figure 5 shows one possible layout based on a 9.25 c/c grid running North – South.

The other major issue is the structure and stability of the south elevation, which was previously afforded natural support from the floor plates and the overall stability system. The overall stability arrangement will need to be modified and the south elevation itself will now create additional issues.

The south elevation's columns will now span the full building height without intermediate support from the floors and the whole elevation will link to the main structure at roof level (potentially with roof bracing depending on whether we assume a solid or glass roof).

It's completely inadequate to just provide a few bland statements about checking structural sections for new loads (which is what many candidates did).

Summary

This question is relatively straightforward, with some clear constraints on column spacings, storey heights and perimeter limitations, which should have provided an ideal question to demonstrate an understanding of structure behaviour, particularly in relation to alternative stability systems. There are however areas where the brief needs to be interpreted, with different structural implications depending on what is assumed/decided. This can be turned to your advantage by discussing the issues and the options afforded by each choice/assumption.

Because of its relative simplicity, it's even more important with this question to fully develop clear "distinct and viable" alternatives utilising all possible attributes (column layouts, stability systems etc), a full analysis of the merits of each option and a clear understanding of the structure's behaviour. Many candidates offered no more than slight variation between schemes based only on alternative column layouts, even though there are clearly alternatives available (stability systems and possibly foundation arrangements). This was an ideal vehicle to demonstrate an understanding of structure behaviour and to propose different structural arrangements.

All-in-all this is a fundamentally straightforward question that should have been ideal for a competent, experienced candidate, who could have concentrated on demonstrating an understanding of structure behaviour and an ability to conceptualise different arrangements.

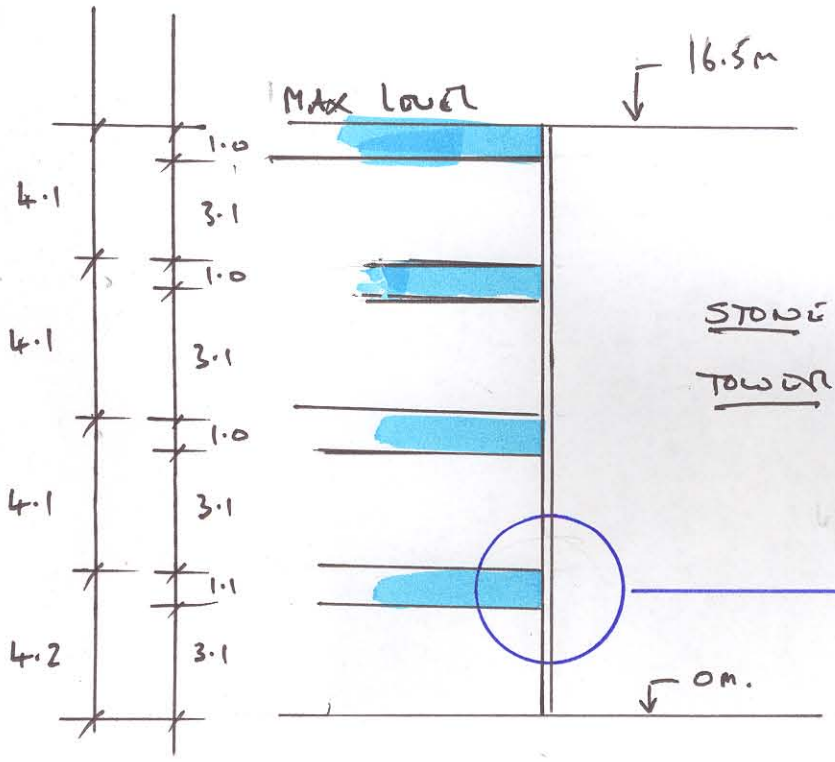


FIG 1. FLOOR HEIGHTS.

SLENDER FLOOR REQUIRED

$\therefore \frac{SPAN}{DEPTH} \simeq 15-20.$

say $\frac{8000}{15} = 530$ mm.

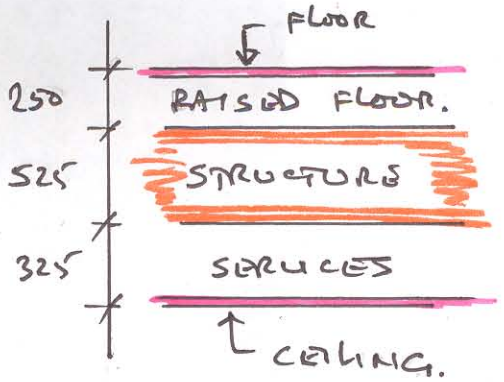


Fig 1(a) FLOOR ZONE.

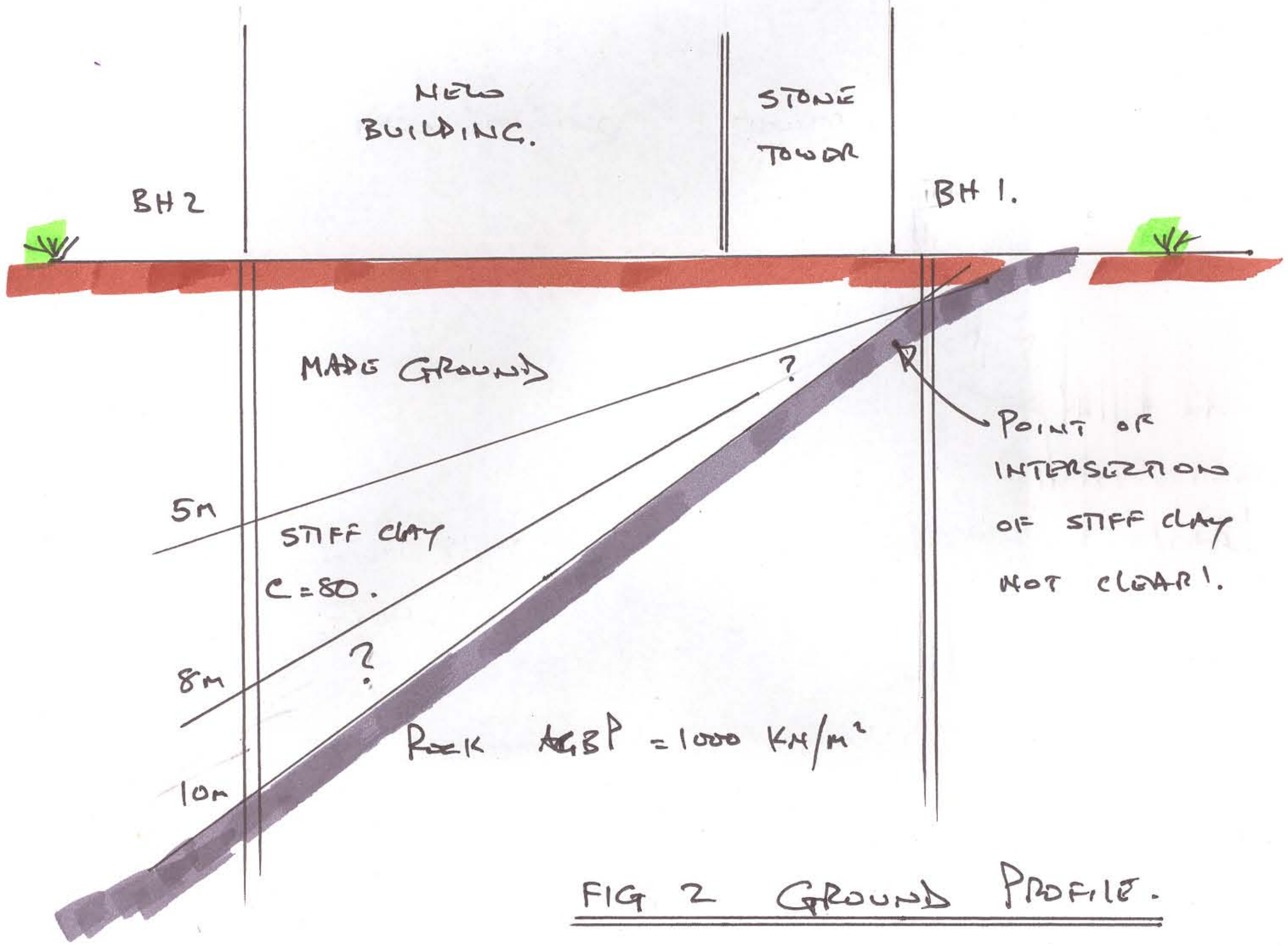
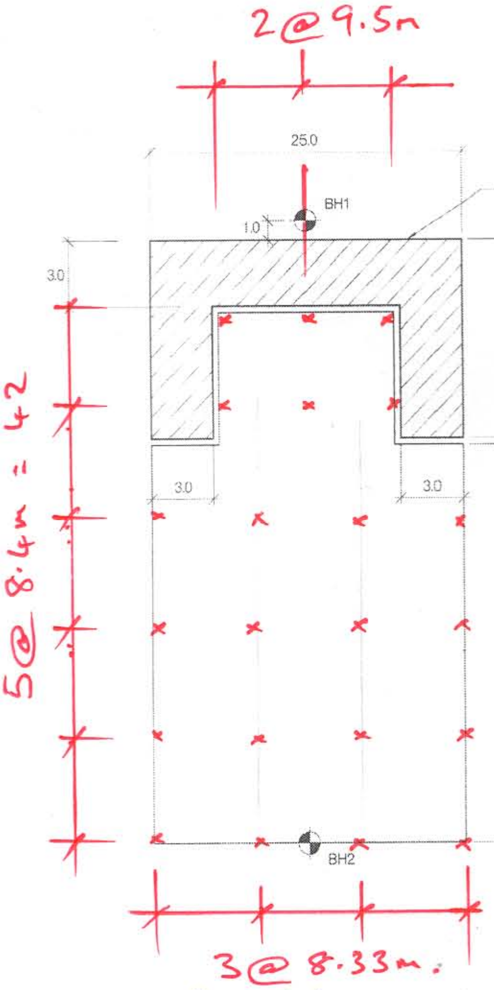
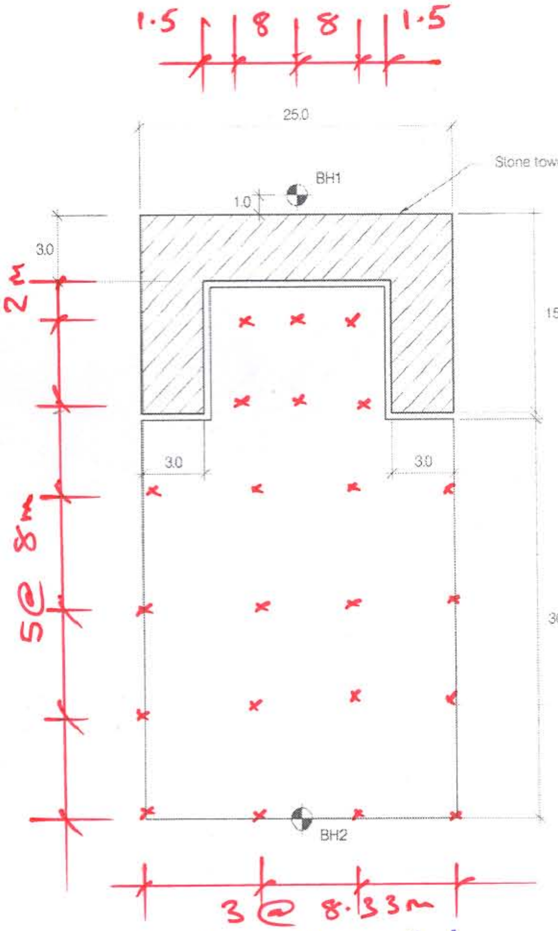


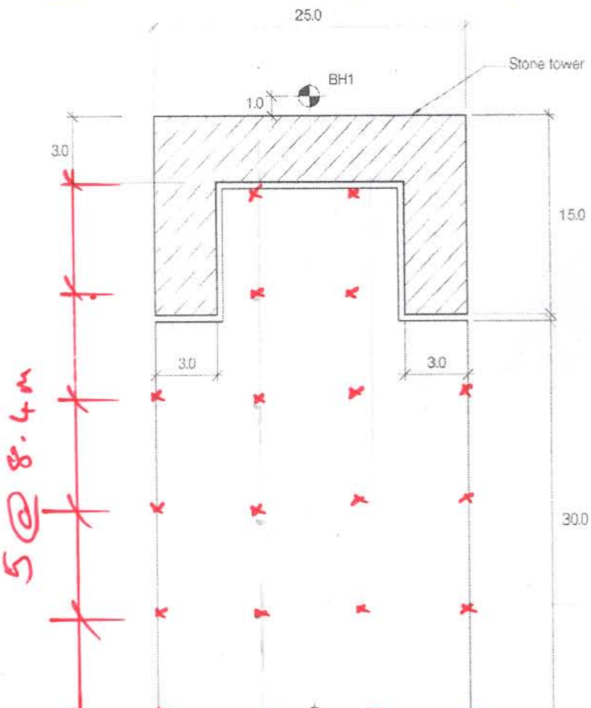
FIG 2 GROUND PROFILE.



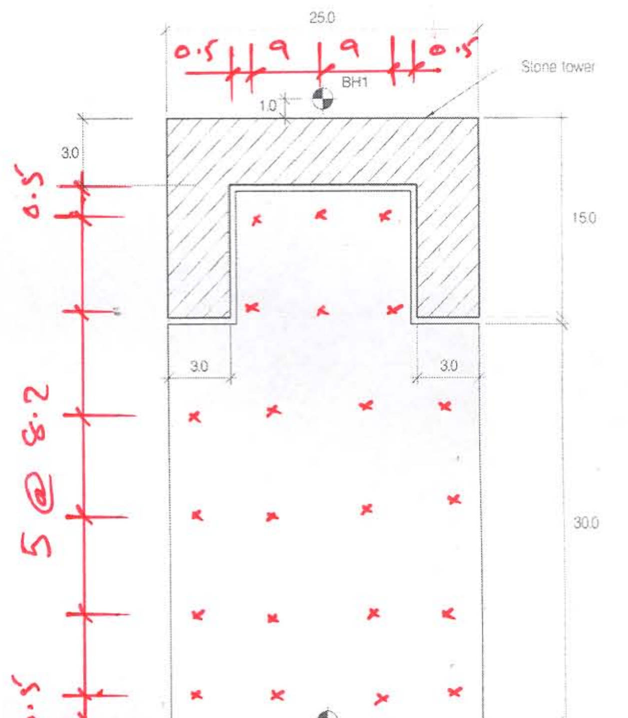
Option 1. Columns evenly spaced simplest option



Option 2. Columns kept away from tower



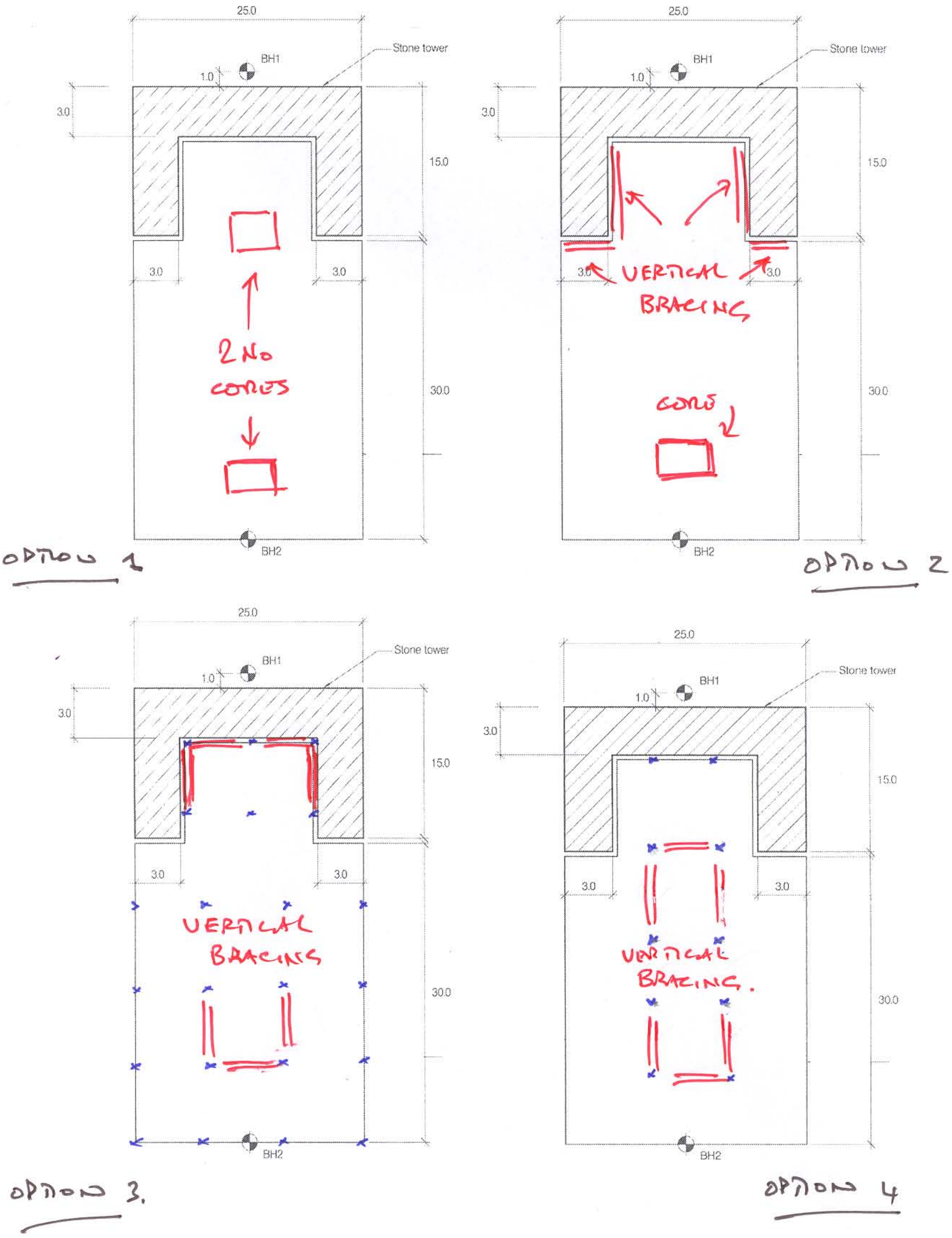
Option 3. Columns evenly spaced to minimise floor spans BUT cantilevers by tower.

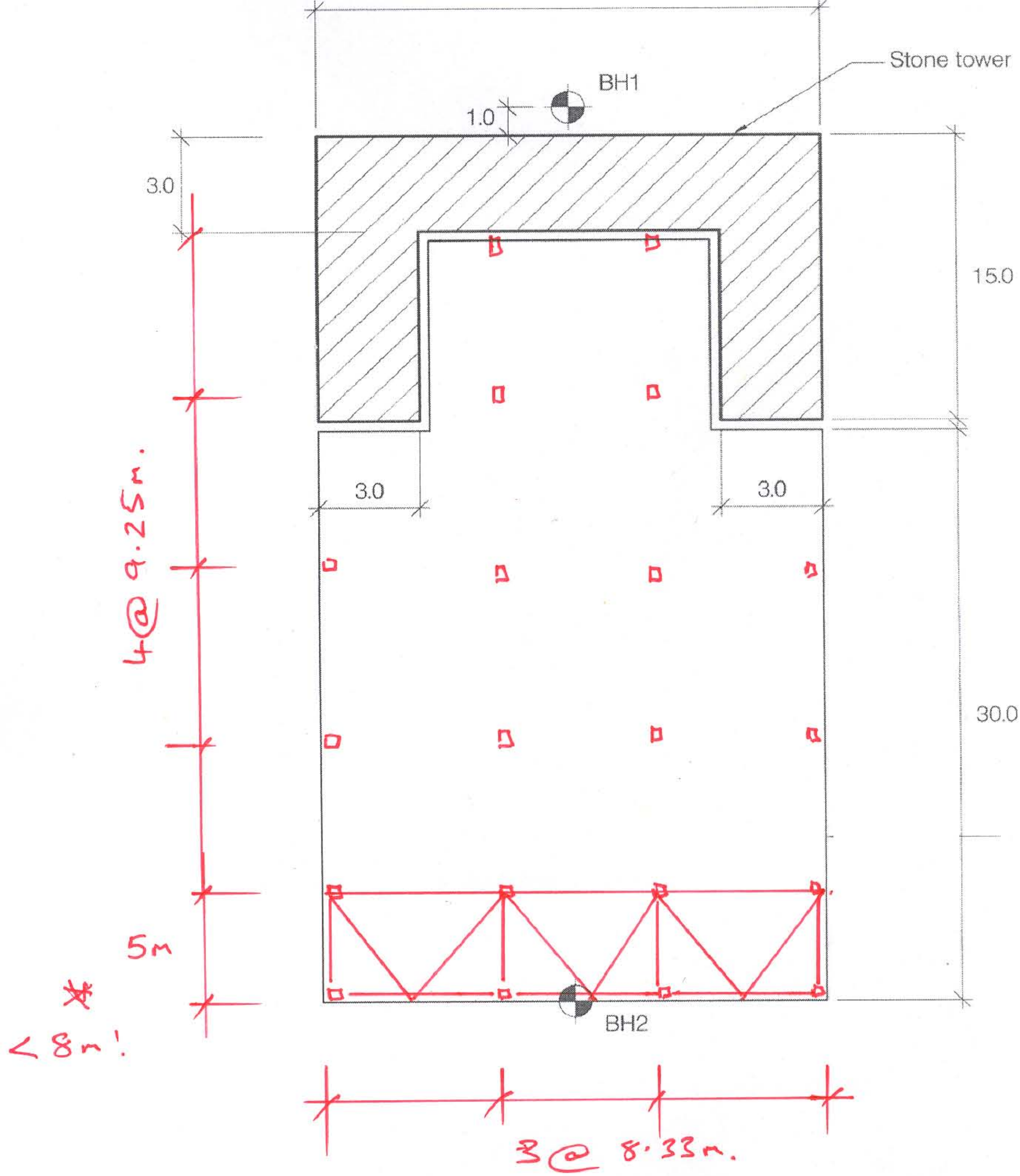


Option 4. Columns inset by 0.5m for architectural effect.

FIG 3: Four possible column layouts.

FIG. 4. FOUR POSSIBLE STABILITY LAYOUTS.





- Grid layout in response to client change (letter).
- option assumes column spacing criteria relaxed.
- Full height columns on Southern elevation.
- Roof bracing supports & stabilizes column heads

FIG 5: REVISED LAYOUT IN RESPONSE TO CLIENT CHANGE

The Institution of Structural Engineers

Possible solution to past CM examination question

Question 4 - April 2009

Commercial Building

by Bob Wilson

Question 4. Commercial Building

Client's requirements

1. A seven-storey commercial building on a square site 45.0m x 45.0m: see Fig. Q4.
2. The facade at the south-east corner is to be inclined between level 2 and the roof. All other facades are to be vertical. All facades are required to be fully-glazed between level 2 and the roof.
3. To provide flexibility for building entry points, the clear distance between external columns on level 1 must be a minimum of 8.0m. External columns on level 2 and above, if required, must be evenly-spaced. No column is permitted on any level at the north-west corner of the building.
4. Neither external nor internal structural walls are permitted. A clear distance of at least 7.0m is required between an internal column and any other column or external enclosure. The service cores are to be structurally independent of the main building.
5. No foundations may extend beyond the site boundary.
6. Allowable structural floor zones are:
   Level 2: 1.7m
   Other levels and roof: 1.2m
7. A minimum fire resistance of 2 hours is required for all structural elements.

Imposed loading

8. Roof 2.5kN/m²
   All floors 5.0 kN/m²

Site conditions

9. The site is level and is located in the suburban area of a town 200km from the sea. Basic wind speed is 40m/s based on a 3 second gust; the equivalent mean hourly wind speed is 20m/s.
10. Ground Conditions

Ground level – 2.0m	Loose fill
2.0m – 5.0m	Sandy gravel. N varies from 10 to 20
5.0m – 8.0m	Weathered rock. Allowable bearing pressure 500kN/m²
Below 8.0m	Rock. Allowable bearing pressure 1500kN/m²

Ground water was encountered at 2.5m below ground level.

Omit from consideration

11. Detailed design of the service cores.

SECTION 1 (50 marks)

a. Prepare a design appraisal with appropriate sketches indicating two distinct and viable solutions for the proposed structure including the foundations. Indicate clearly the functional framing, load transfer and stability aspects of each scheme. Identify the solution you recommend, giving reasons for your choice. **(40 marks)**

b. Before construction begins, a group of piles forming the foundations of a previous building on the site are discovered. The group comprises 49 concrete piles each 600mm diameter in a 7 x 7 grid spaced at 3.0m centres in both directions and the centre of the group is located at the north-west corner of the site. The client wishes to know whether the piles can be re-used. Write a letter to the client advising him of the implications of the discovery and the practicality of re-using the piles. **(10 marks)**

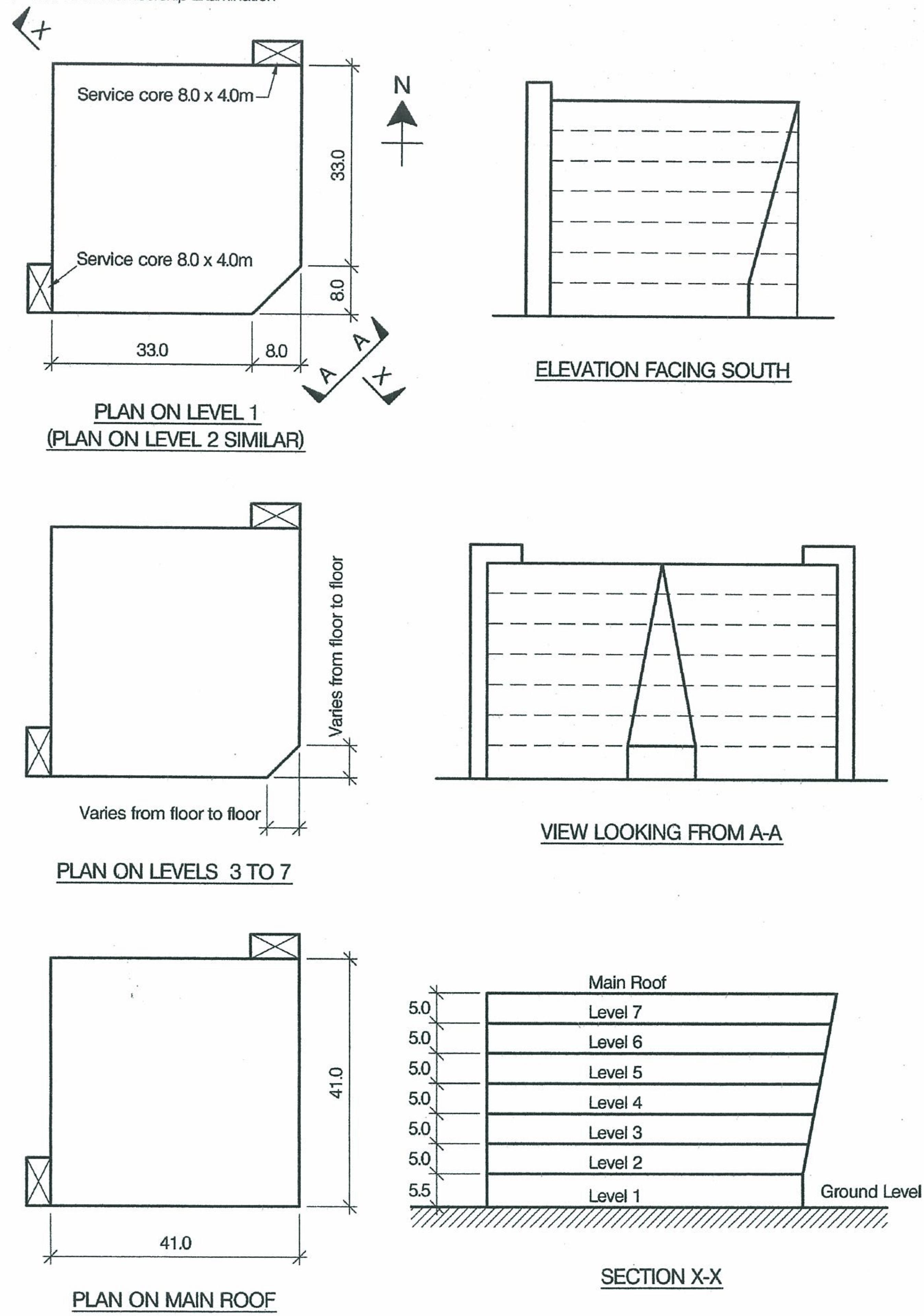
SECTION 2 (50 marks)

For the solution recommended in Section 1(a):

c. Prepare sufficient design calculations to establish the form and size of all the principal structural elements including the foundations. **(20 marks)**

d. Prepare general arrangement plans, sections and elevations to show the dimensions, layout and disposition of the structural elements and critical details for estimating purposes. **(20 marks)**

e. Prepare a detailed method statement for the safe construction of the building and an outline construction programme. **(10 marks)**



NOTE: All dimensions are in metres

FIGURE Q4

Fig. 01

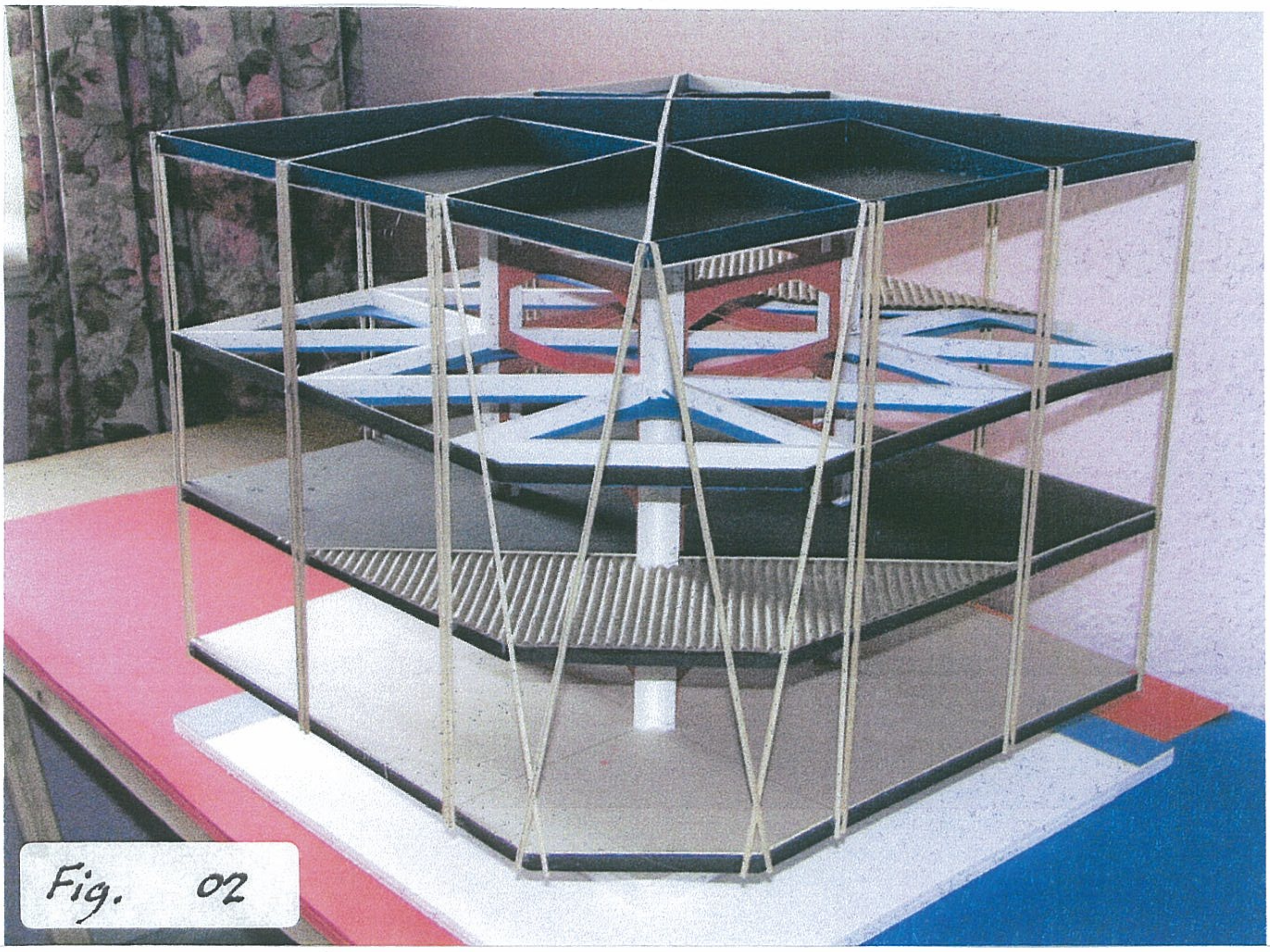


Fig. 02

Question 4 - Commercial Building: 2009 relates to a seven-storey building on a square site. Figures 01 and 02 show two distinct and viable solutions, as required by Section 1a.

Figure 01 shows the basis of Option 'A', though it should be noted that several of the floor slabs have been left out of the model for simplicity. The basis of the option is the use of square, flat slab panels supported on columns. It is essentially a reinforced concrete solution.

Because the south-eastern corner façade is inclined and the floor slabs cut back progressively from the top floor [Level 7] to Level 2 there cannot be a corner column.

Client's requirement number 3 does not allow a column at the north-western corner of the building.

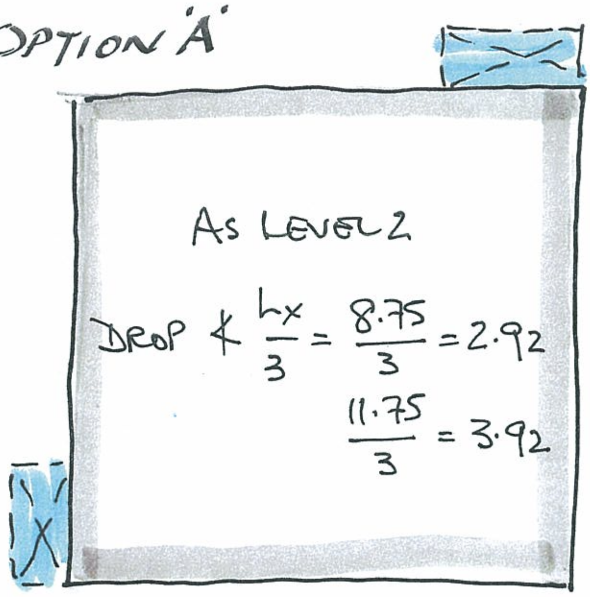
Consequently, this design has no column at any of the corners. Instead, the floor edges are supported by a tension tie, itself supported at roof level by an upstand edge beam. This beam cantilevers over the supporting column, and the structural framing has been featured (see Figure 01).

Figure 02 illustrates Option 'B' where a group of four columns forms a stifly-braced "core" up the middle of this building. A grid of steel girders at roof level supports hangers around the perimeter that, in turn, support the free ends of the local floor beam grid. Note that alternate floors have been omitted on the model for simplicity.

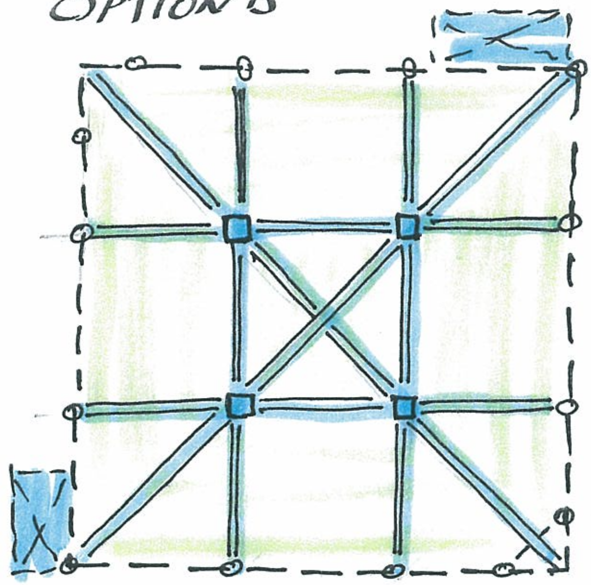
RAW

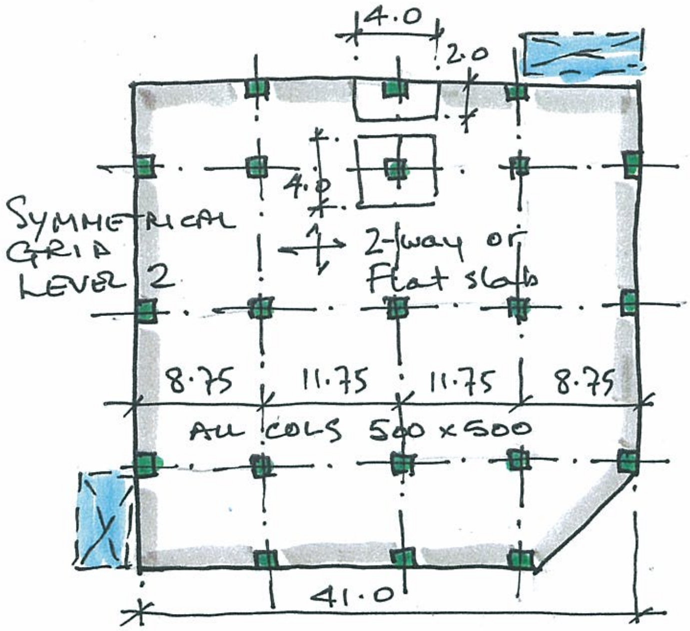
The Client's requirements numbers 3 and 4 dictate the grids:

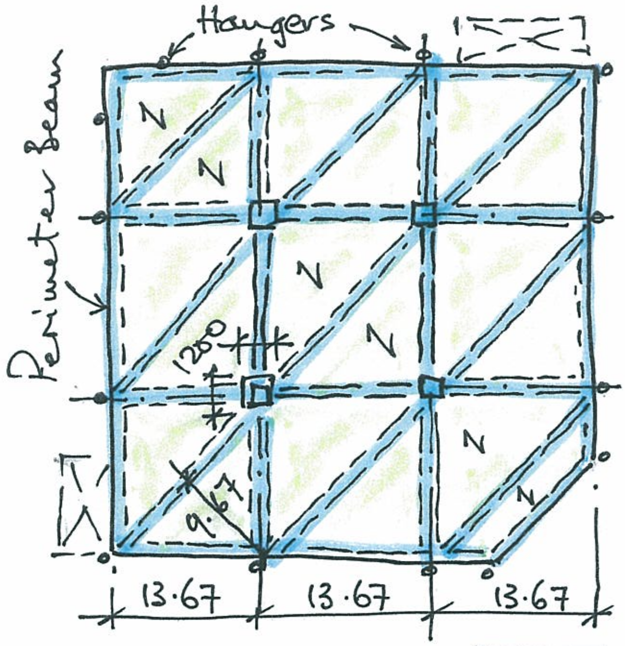
OPTION 'A'

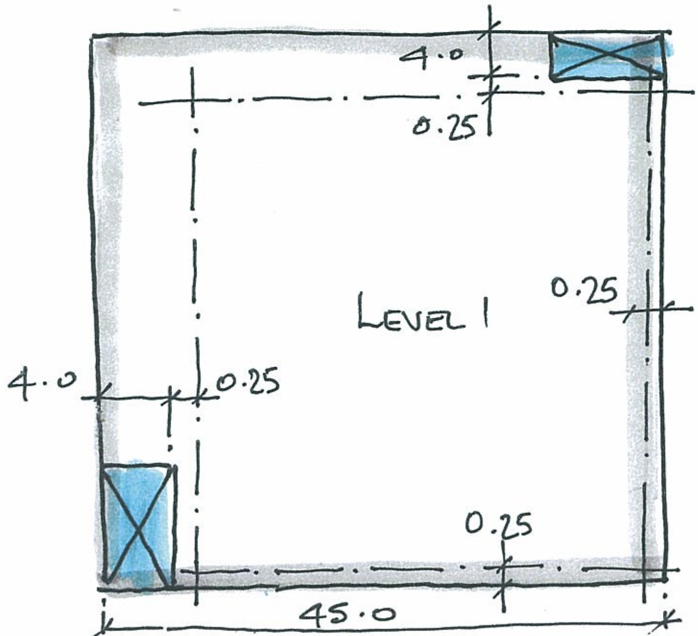


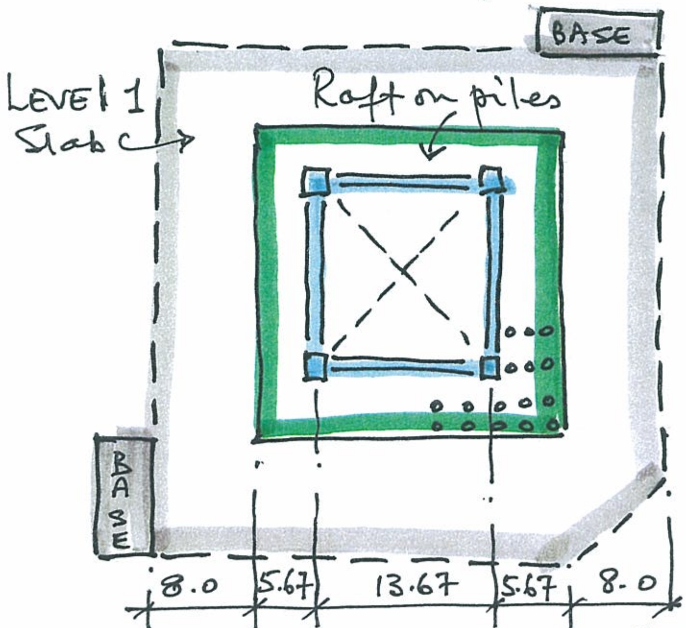
OPTION 'B'











RAW

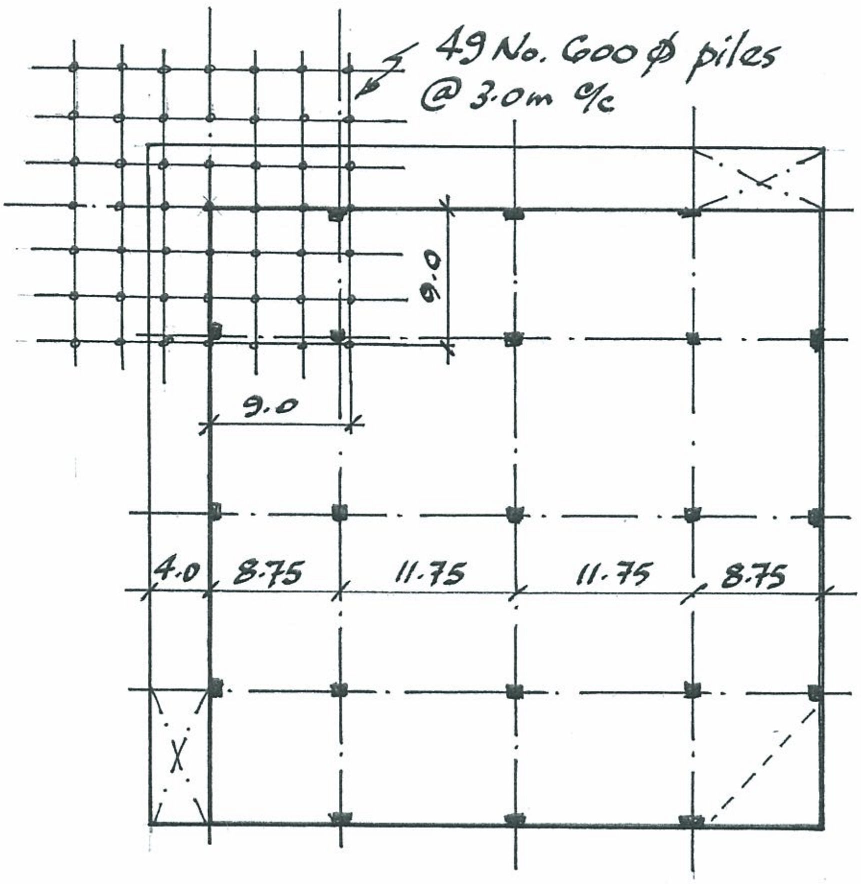
One element of the "distinctness" emerges immediately — the slab spans are different. After that one thing leads to another ...

Option A can use 2-way or flat slab principles. The flat-slab choice would probably have drop panels to take the punching shear. These are indicated in Figure 01 at all seven floors and look strange when isolated! The columns are sized 500 x 500 so that the grid can be calculated. This size seems to be credible though no loads are known yet. The capacity can be adjusted using a suitable grade of concrete and varying amounts of rebar. Although redistribution of moments may be permitted the candidate probably won't have time to do the calculations and it is doubtful that there will be marks available for this sophistication. The "simple" method of calculation allowed in BS 8110 is appropriate because there are more than three bays in each direction.

Clearly this is a "moment frame" and stability is achieved by the stiff joints at each level. Consequently the columns need additional strength, above the axial capacity, to take moments. If the candidate decides to prepare calculations using "column charts" a reference needs to be given.

Section 2c - calculations should include reinforcement for a "typical" panel, an internal column and its foundation. It seems likely that individual pads on mass-concrete piers founded in the sandy gravel would carry the load. If possible the candidate should "reserve" piling for Option "B". The Level 1 slab would be "ground bearing" on compacted granular fill. The service cores might be able to stand on this slab without deeper foundations.

It is worth looking at Section 1b at this point:



"Before construction begins, a group of piles... are discovered. The centre of the group is located at the north-west corner of the site."

It is absolutely necessary for the Engineer to plot the pile positions relative to the proposed building – in this case Option 'A'. Although I tried to draw this plan "freehand in good proportion", in the end it was quicker to draw the plan to scale [above]. The group of piles only affects 3 columns because no column is allowed at this corner [Client's requirement number 3].

One must assume that the piles go down 8.0m to rock and that none of the piles are compromised in any way ["necking", "void at the base", "lack of compaction", etc.]

RAW

With this assumption it should be possible to substitute piles for two or even all three mass concrete piers under these column positions.

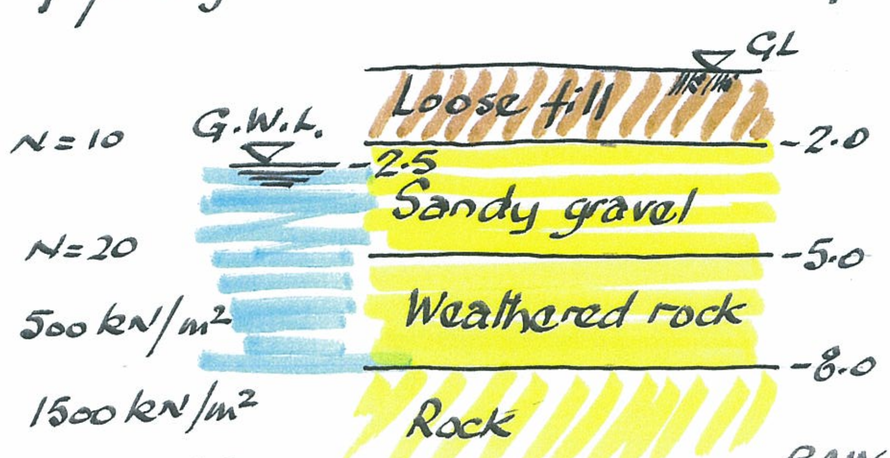
However, the relevant piles would need to be investigated in order to confirm that they are suitable, and the three column bases would need to be tied together with ground beams to eliminate the effects of eccentricity – the loads do not coincide with the axes of the piles. Whether there would be any cost benefit is doubtful. The programme might be affected – lengthened – too.

The contractor may prefer to excavate and "clear" the affected areas under the columns and proceed with the planned foundations.

In any event the 25 piles located under the ground floor [Level 1] slab would all need to be cut down into, say, the sandy gravel and backfilled with the rest of the site [removal of the existing loose fill, or its compaction] with selected granular material compacted in layers. The quality of the "Loose Fill" is unknown and may be contaminated with plaster [gypsum attacks concrete] and/or timber, etc.

All things considered, it is unlikely that the pile group can be beneficially used. However, it is a warning because if previous foundations needed piling perhaps the use of piling should be considered for the new works.

GROUND PROFILE



RAW

Section 1a always includes "the foundations" in the text specifically to remind the candidate of the need to spend time on them. The foundations for Option 'A' can be expected to be different from those for Option 'B'! It can be a bad mistake to "save time" by making them the same.

The ground profile shown on page 06 has a ground water level at −2.5m, only 0.5m below the nominal top of the sandy gravel. The average 'N' value is 15 – indicating a possible bearing capacity of 150 kN/m², but the high GWL will halve this value to 75 kN/m². It will be more efficient to found on the weathered rock at 500 kN/m² or even the rock at 1500 kN/m² – the problem will be to excavate through the waterlogged sandy gravel.

An approximate column load will indicate the pad area that will be necessary – but do not expect many marks for this work since Section 2c is where these are available for calculations. If you feel unsure about specifying foundations without an estimate of load the following might be done:

Imposed load per floor	5.0 kN/m²
Permanent load per floor (say) ($11.75/_{24} \times 24$)	12.0 kN/m²
	17.0 kN/m² × 12 × 12
	= 2448 × 7 levels incl. roof
	= 17136 kN [unfactored]

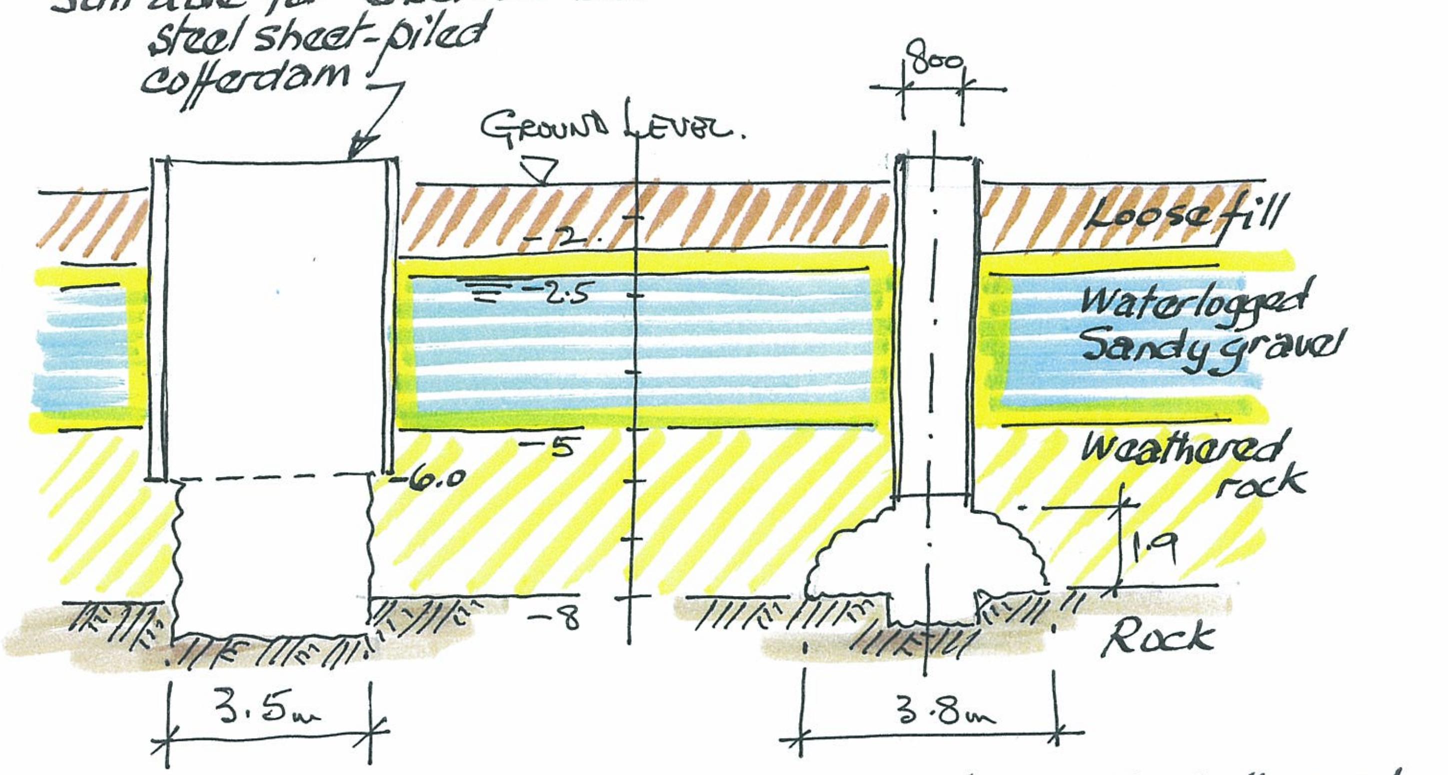
$$\text{Area} \simeq \frac{17136}{500} = 34\,m^2$$

$$\text{or } \frac{17136}{1500} = 11.5\,m^2$$

"Site conditions" number 10 quotes "<u>allowable</u>" bearing pressure

RAW

A square pad 6m × 6m provides 36m² but the pads would touch [column spacing only 11·75m].
A square pad 3·5 × 3·5m provides 12·25m² and is credible.
A 3·8m diameter "base" provides 11·34m² but is too big for a single caisson pile [realistic diameters range between 600mm dia and 2400mm dia, although the largest machines can dig pile shafts up to 4·57m diameter – ref. Tomlinson "Foundation design and construction", 7th Edition, I.S.BN-13: 978-0-13-031180-1; probably one of the books you will consider taking into the examination with you!]
"Belling buckets normally cut base diameters up to 3700mm, although diameters of as much as 7300m are possible..."
so the 3·8m diameter is credible using an 800mm diameter shaft under-reamed or belled out in the weathered rock which is 3·0m nominal thickness. Water would be controlled by using casing and/or bentonite. The following would be suitable for Section 2e.

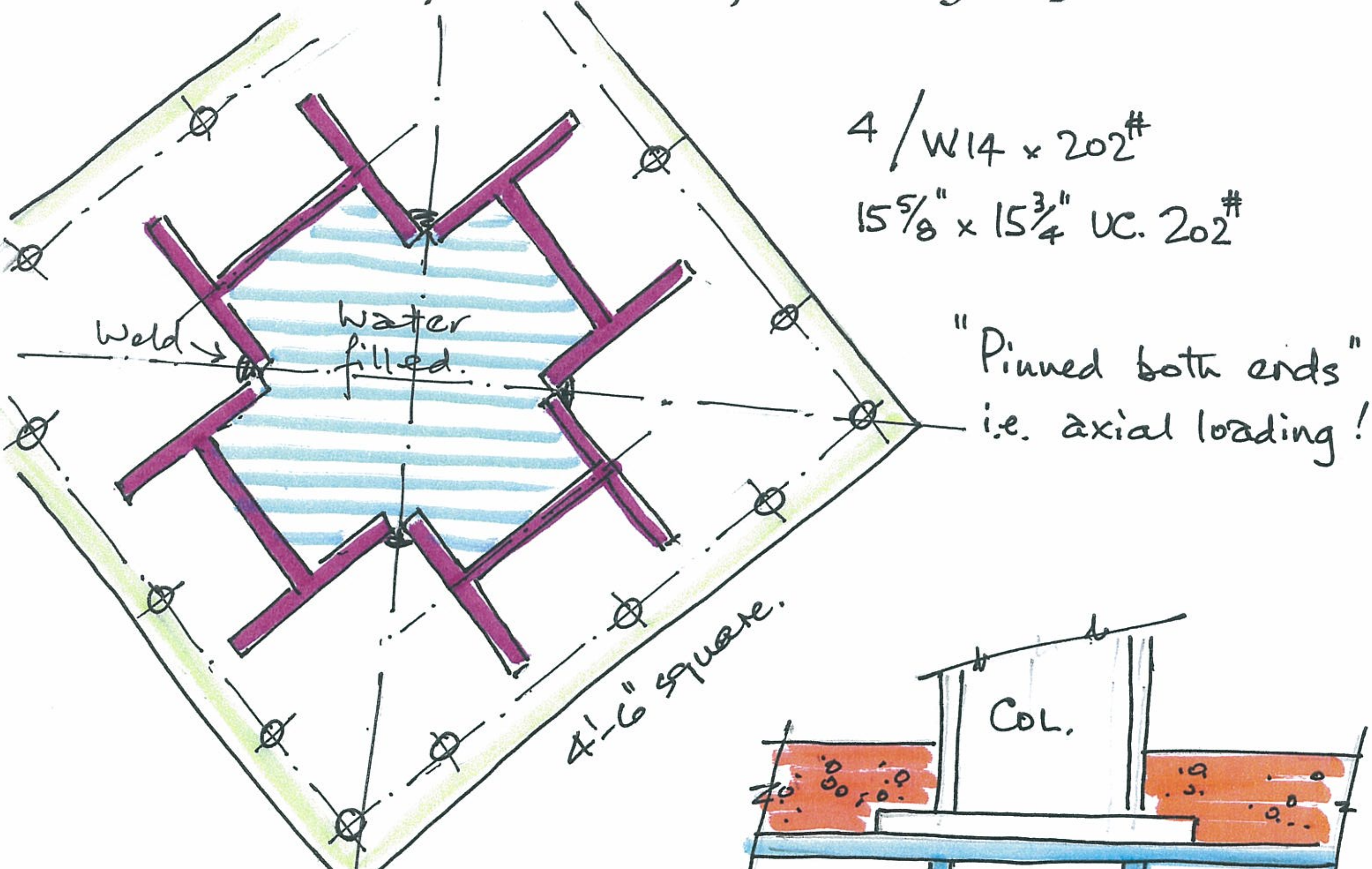


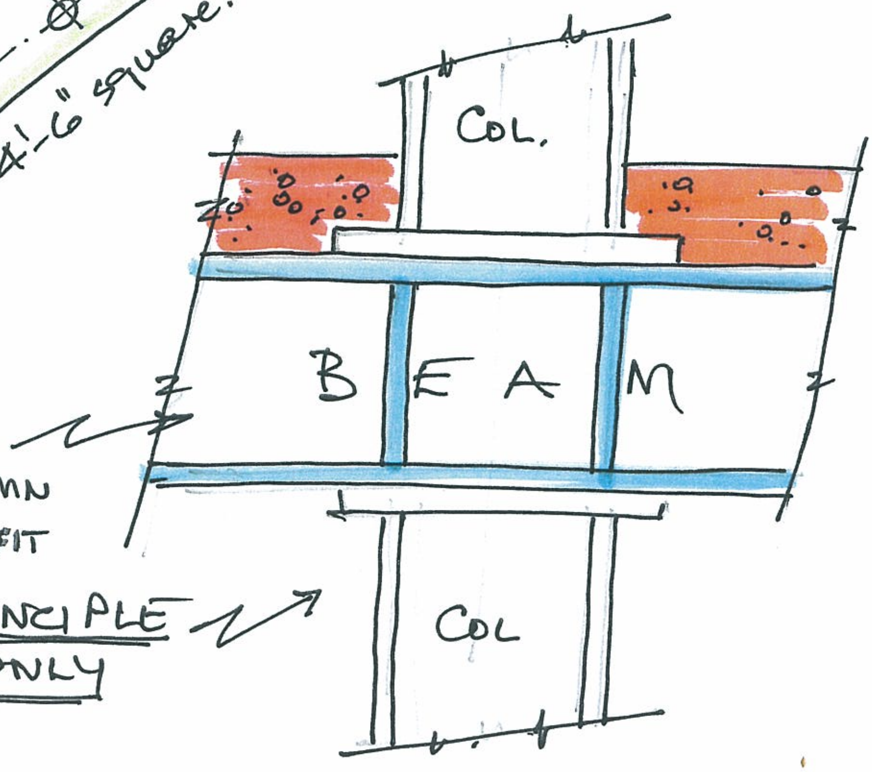
Steel sheet piling driven into weathered rock surface. Soil excavated from G.L. by backacter. Concrete placed by pump or tremie if flooded. No man entry.

800mm dia. bored pile shaft cased through waterlogged sandy gravel. Under-ream or Bell formed at rock level into weathered rock. Shaft will probably flood. Ready mixed concrete placed by tremie. No man entry.

RAW

Option 'B' is essentially a compression "core" with a massive cross-shaped roof suspension system from which the floor edges are hung. The floor slabs span in a diagonal direction [see page 03] onto diagonal secondary beams. This reduces the potential span from 13.67m to 9.67m or less. The whole frame uses structural steel with profiled steel decking topped with concrete. The dominant central "core" comprises four fabricated stanchions made up from Universal column sections welded together. The hollow-section stanchion will be protected from fire by being filled with water [with full header expansion system].

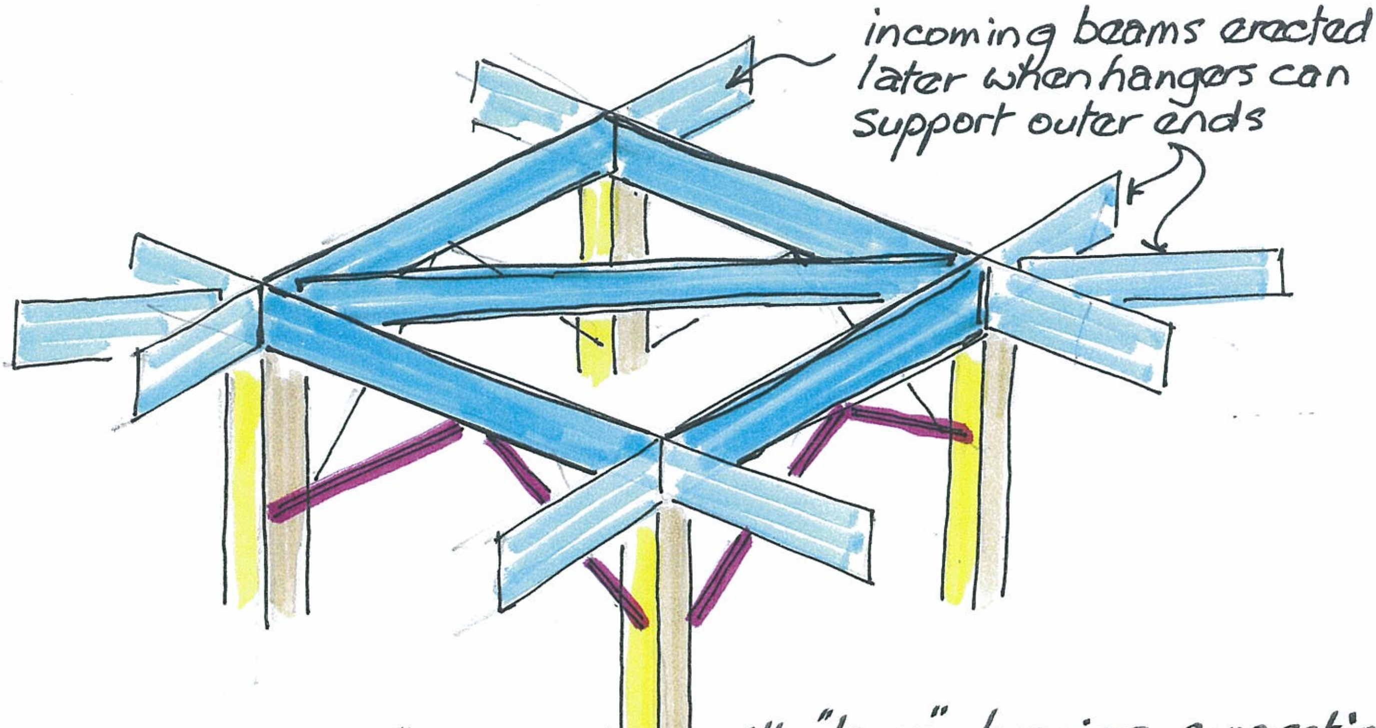




BEAMS RUN THOUGH COLUMN SPACE IN ORDER TO BENEFIT FROM CONTINUITY.

PRINCIPLE ONLY

RAW



Each "portal" is braced with "knee" bracing connecting the stanchion to the beam grid. Thus, the erection proceeds up the core from floor to floor.

The beam sizes can be sized at this stage by "guesstimation" or later in Section 2c by more precise calculation. However, it is more important at this stage to communicate the "conceptual ideas" rather than the details.

Consequently, I shall move onto the roof suspension system:

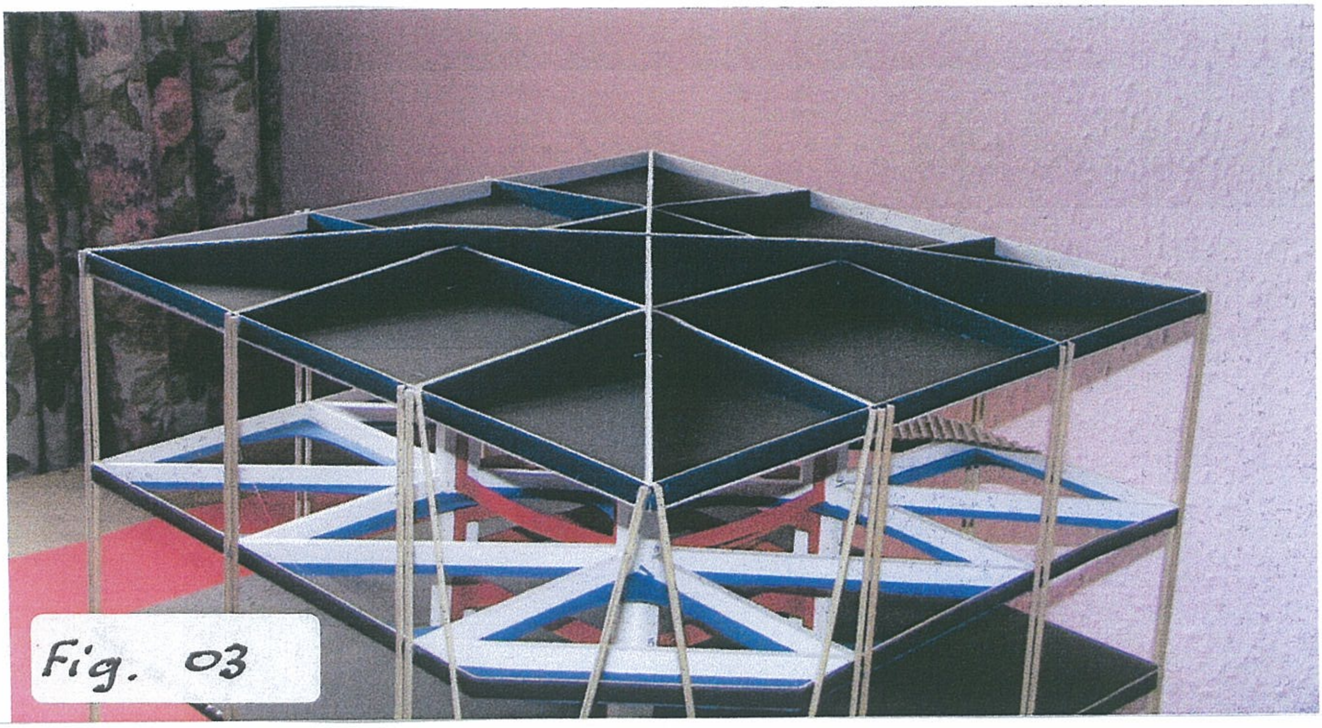
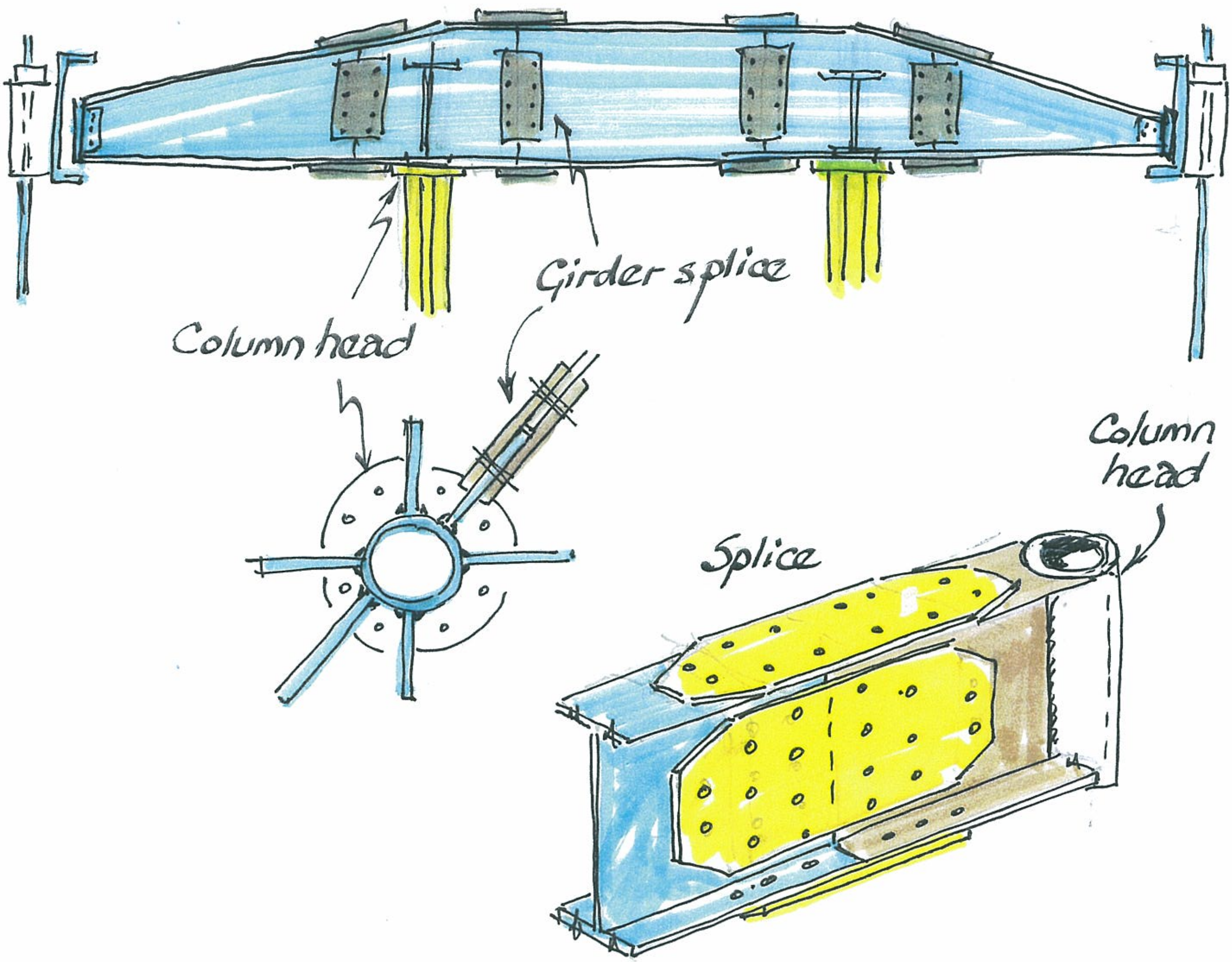


Fig. 03

There are two intertwined suspension systems – the first supports the four corners and runs diagonally – the second supports the intermediate hangers along the sides and is on the regular grid. Around the edge there is an upstand girder. The hangers are attached to the upstand. The hangers are twinned in order to provide a "fail-safe" mechanism – one hanger can fail completely in each pair without causing catastrophic failure. the hangers at the south-eastern corner splay apart in order to pick-up the edges of the curtailed slabs below.

The intersections of the girders occur above the column heads. Each girder needs to be transported and assembled so the girders must be fabricated in sections. Splices can be located at the intersections.



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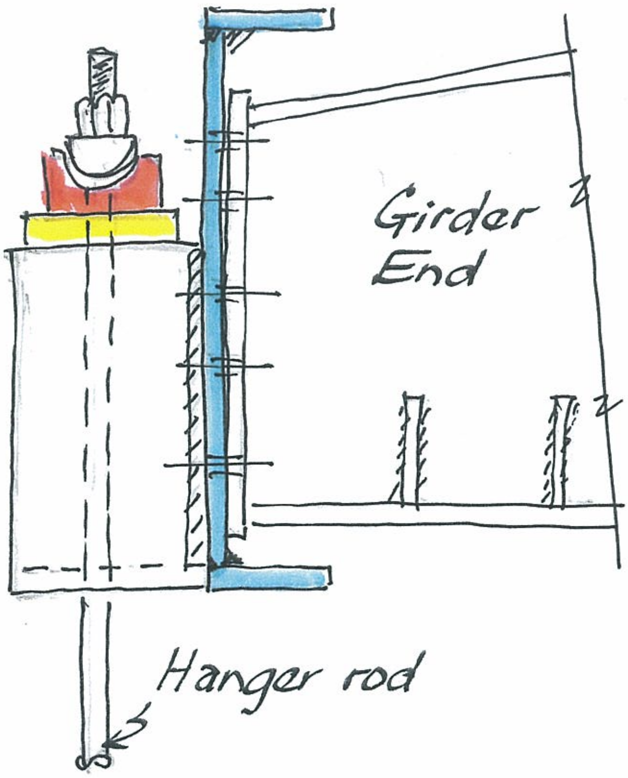
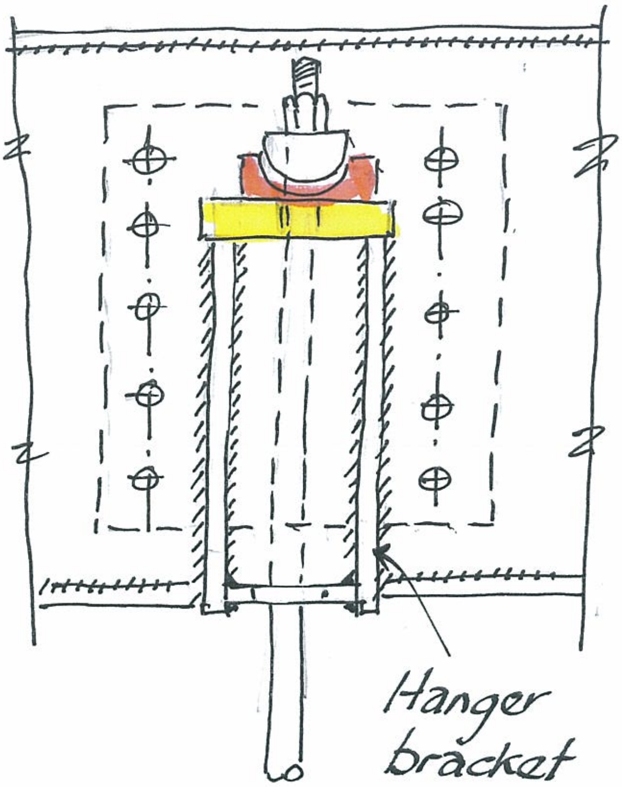
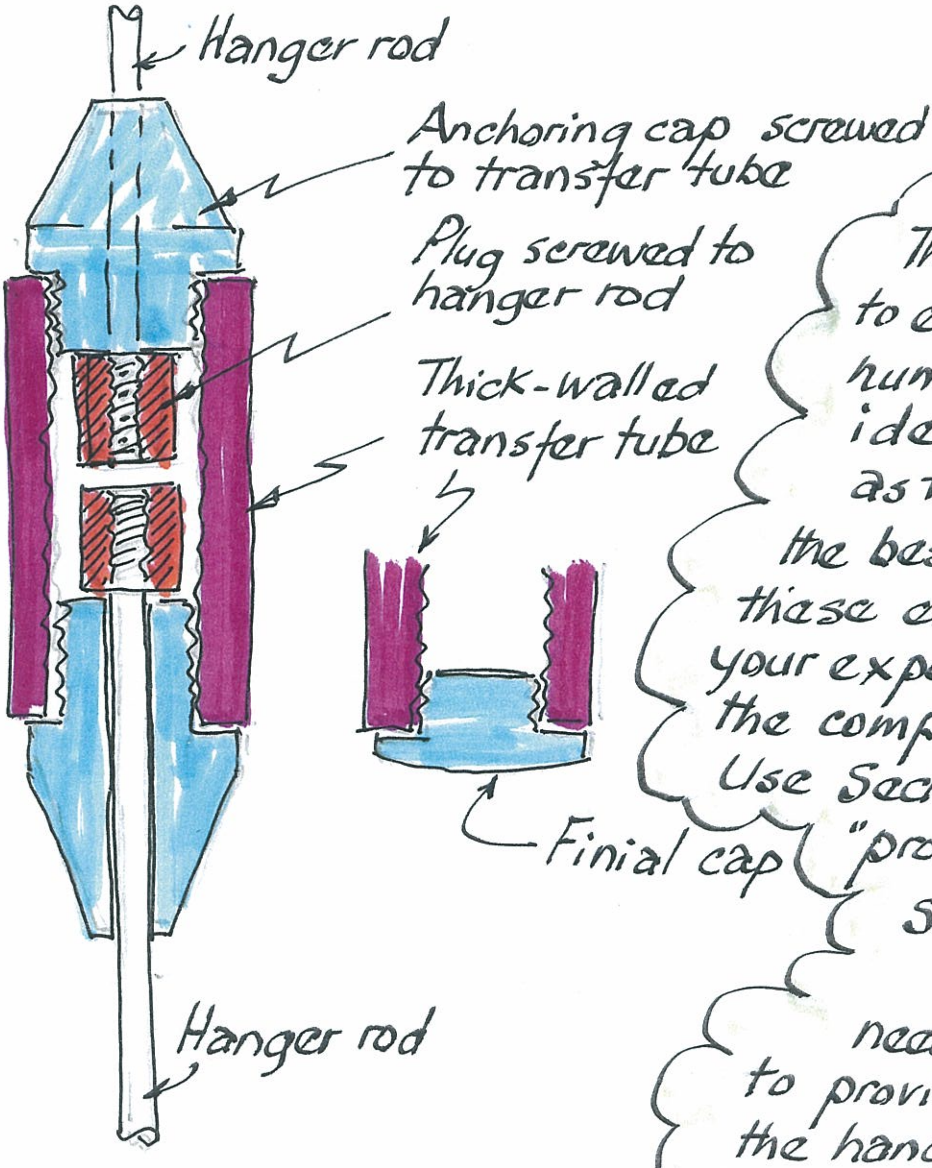


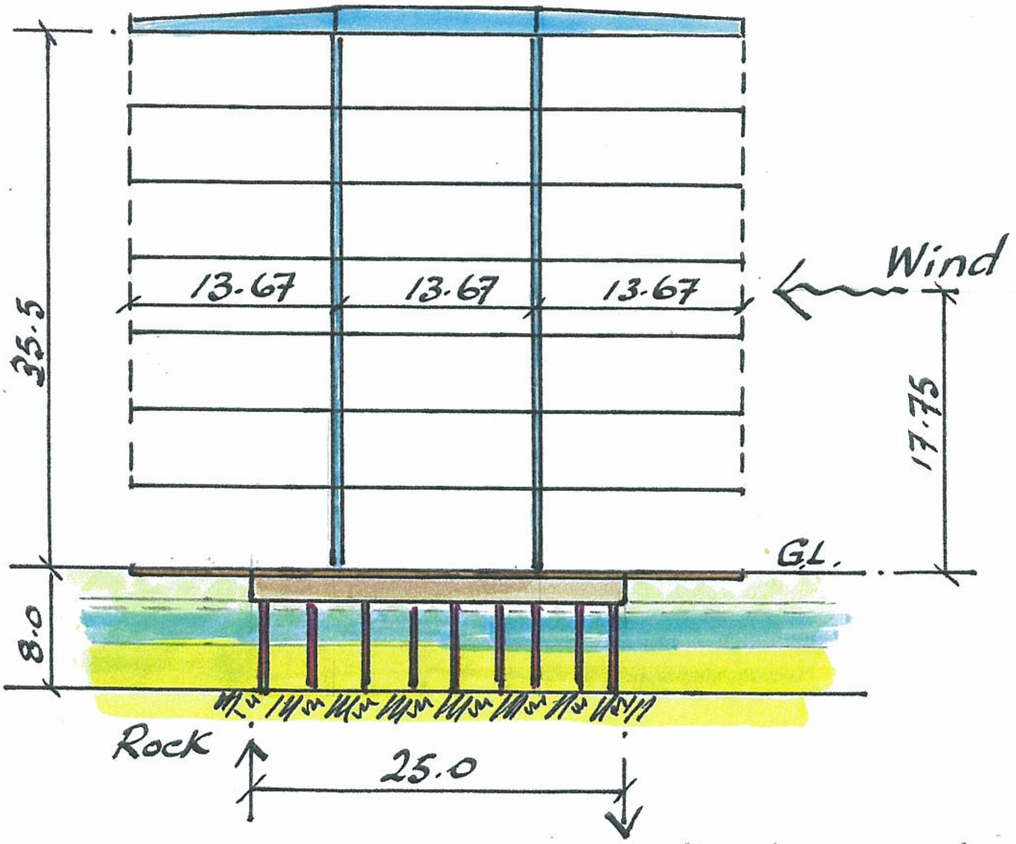




This Option needs to explain quite a number of conceptual ideas. Sketches such as these are probably the best way to make these explanations. Use your experience to draw the components in proportion. Use Section 2c for the "proof" calculations.

Several of the Conceptual Ideas need a "proof" calc. to provide a size, e.g. the hanger rods.

With reference to the Level 1 slab plan on page 03, the core will be supported on a piled raft, with the piles carrying the concentrated load directly to the bedrock stratum. This foundation must be stable under direct loads and overturning conditions



Let wind pressure $= 1.2\ kN/m^2$ [$\equiv 1.0 \times 1.2$ factor]

Wind Moment $= (1.2 \times 35.5 \times 41) \times 17.75 = 31010\ kNm$

Gravity load (see page 07) $= 7 \times 41.0 \times 41.0 \times 17.0\ kN/m^2 = 200\,000\ kN$

Pressure on bedrock $= \frac{W}{A} \pm \frac{M}{Z} = \frac{200000}{25.0 \times 25.0} \pm \frac{31010}{25.0^3} \times 6$

$= 320\ kN/m^2 \pm 12\ kN/m^2$

$= +332\ kN/m^2 < 500\ kN/m^2$

or or

$+308\ kN/m^2$ $1500\ kN/m^2$

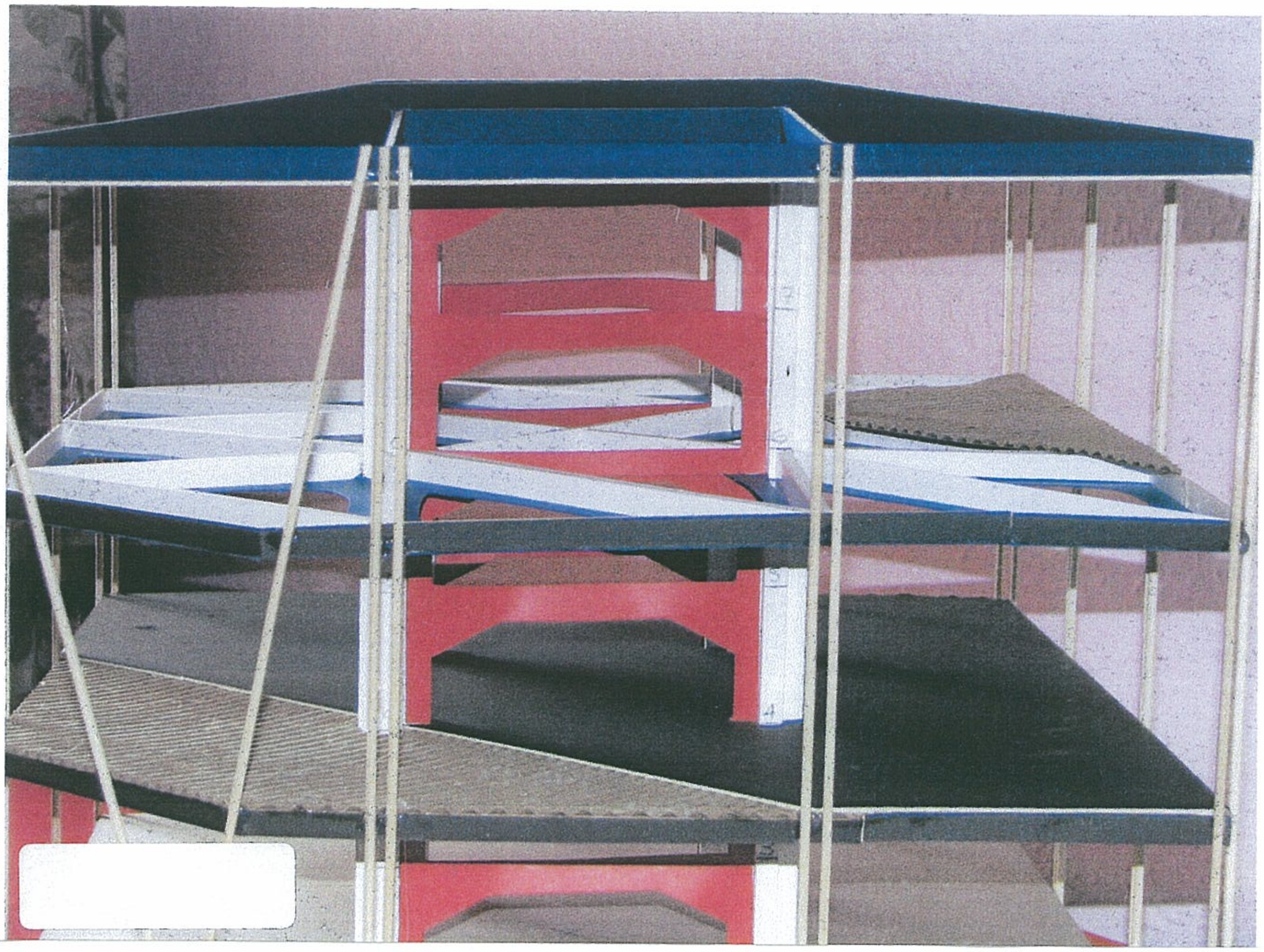
There is no uplift.

The four column loads [approx 50 000 kN each] will need to be dispersed through the raft-type pile cap - provisionally shown as 2.0 m thick.

If this option is chosen for the final proposal then Section 2c will contain a number of important calculations. Check back to the question: "Prepare sufficient design calculations to establish the form and size of all the principal structural elements including the foundations."
Any design calculations already done in Section 1'a' and 'b' will have been marked and cannot be marked again in Section 2c! It is important that the design calculations cover new ground and develop the proposal in a positive way. It is unlikely that calculations for the composite "tin deck" will add anything to an answer obtained using manufacturer's data. On the other hand the roof girders, main stanchions and hanger rods are unique to this option and need to be "sufficiently" calculated – not in the minutest detail!
The foundations use a raft and piles – "sufficient" calculations are needed for both.
Again, when it comes to Section 2d any details already marked under Section 1a cannot be marked again unless significantly developed, e.g. by being drawn to scale and dimensioned so that the Q.S. can use them for estimating purposes. Effort should be concentrated on the G.A. drawing for the roof and typical floor, and the foundations. A cross section through the building and details of typical cladding and weatherproofing are needed.

Section 2e requires a detailed method statement and an outline construction programme. There are only 10 marks, indicating about 40 minutes work. It is probable that the examiner has provisionally allocated the marks in the proportion 6:4; "provisionally" in the sense that good work will be rewarded even if time appears to have run out and the programme is unfinished.

The Engineers Method Statement highlights the construction actinFies that might influence the estimate of costs. In Option "A", a concrete construction, once the foundations have been finished (see page 08) the columns and slabs will follow conventional reinforced concrete practice of setting-up falsework, laying the slab formwork, assembling the reinforcement and placing and curing the concrete. The concrete will probably be supplied by a ready mix supplyer and pumped up to the working level. The self-compacting mix will need little spreading but will need to be "struck-off" to a level surface using a vibrating screed or "Bunyan striker" (a roller-type screed). The surface needs to be kept moist (not allowed to dry out) and power trowelled to produce the right finish. After the final finish the concrete will need to "cure". If work is to proceed the fresh surface will need to be protected before the next lift of falsework is erected. Proprietary systems like "quickstrike" allows the formwork panels to



be struck without disturbing the propping action of the falsework.

In Option 'B' the constuction of the piles and pile-cap raft should be described, but the main effort dedicated to how the structural steelwork must be erected. The various levels of the core are assembled using a large crane. The roof girders will be delivered in sections, lifted and bolted together. Some "out of balance" effects may develop and need to be considered. Once the main roof-level supports are in place the hanger rods can be hung and the first level of floor girders lifted into place – this will be Level 2. The member to be lifted is rolled into place on Level 1, the crane lowers its hook through the roof-level steelwork to raise the new beam: this will need to be pulled sideways into place. No floor decking can be laid until all the floor beams have been assembled from Level 2 to Level 7. The concrete topping would be supplied ready mixed and pumped into place. The decking will act as permanent formwork.

RAW

The Institution of Structural Engineers

Possible solution to past CM examination question

Question 5 - April 2009

Art Gallery

by Bob Wilson

Question 5. Art Gallery

Client's requirements

1. A two-storey art gallery is to be constructed on a sloping city-centre site containing a buried culvert: see Fig. Q5.
2. Level 1 is to have plan dimensions of 56.0m x 35.0m with columns at a minimum centre-to-centre spacing of 7.0m in each direction. Level 2 is to have plan dimensions of 50.0m x 12.0m with no internal columns. An allowance for lift and stair cores is included within these plan dimensions.
3. The floor-to-floor height from levels 1 to 2, and the floor-to-eaves height from level 2 to the roof is to be 4.5m. A maximum structural zone of 0.75m is permitted.
4. A flat, level access route of minimum width 3m is to be provided around the perimeter of the building at level 1.
5. A single car park with plan dimensions of 20.0m x 50.0m is required.
6. Access to the site is to be provided at the two locations shown on Fig. Q5, one for vehicles and one for pedestrians.
7. The culvert may be built over but may not be diverted and no additional loads may be applied to it either vertically or laterally. No construction may approach horizontally closer than 4.0m to the centreline of the culvert.

Imposed loading

8. | | |
   |---|---|
   | Gallery floors, levels 1 and 2 | 5.0kN/m^2 |
   | Roof | 1.5kN/m^2 |
   | Car park | 2.5kN/m^2 |

Site conditions

9. The site is located in a city 100km from the sea. Basic wind speed is 46m/s based on a 3 second gust; the equivalent mean hourly wind speed is 23m/s.
10. Ground conditions:
    Datum level - 12.0m sandy clay, C =100kN/m^2, Ø=15°
    Below -12.0m rock, allowable bearing capacity = 2000kN/m^2
    Groundwater was found at 3.0m below ground level. The soil strata and ground water level may be assumed to follow the slope of the ground.

Omit from consideration

11. Detailed design of stair and lift cores.

SECTION 1 (50 marks)

a. Prepare a design appraisal with appropriate sketches indicating two distinct and viable solutions for the proposed structure. Indicate clearly the site layout, functional framing, load transfer and stability aspects of each scheme. Identify the solution you recommend, giving reasons for your choice. **(40 marks)**

b. After the design has been completed, the Client advises that he wishes to consider adding a further area of parking of plan dimensions 20.0m x 50.0m. Write a letter to your client advising how this may be achieved. **(10 marks)**

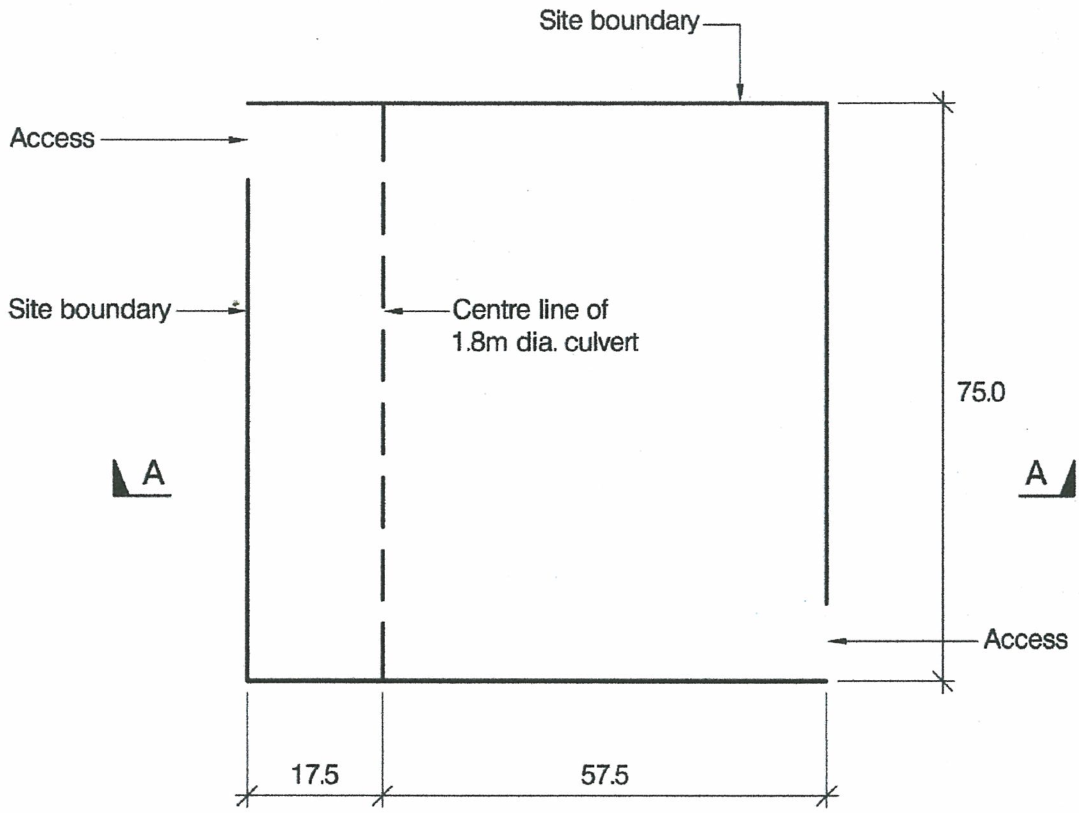
SECTION 2 (50 marks)

For the solution recommended in Section 1(a):

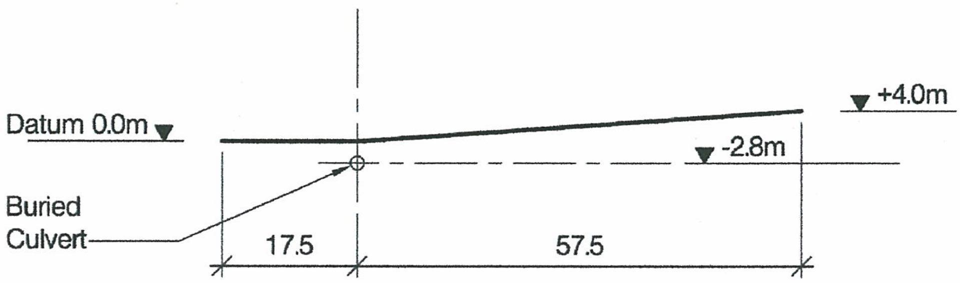
c. Prepare sufficient design calculations to establish the form and size of all the principal structural elements including foundations, any structure associated with the car park and any significant retaining structures. **(20 marks)**

d. Prepare general arrangement plans, sections and elevations to show the site layout, dimensions, layout and disposition of the structural elements and critical details for estimating purposes. **(20 marks)**

e. Prepare a detailed method statement for the safe construction of the building and an outline construction programme. **(10 marks)**



SITE PLAN



SECTION A-A

NOTE: All dimensions are in metres

FIGURE Q5

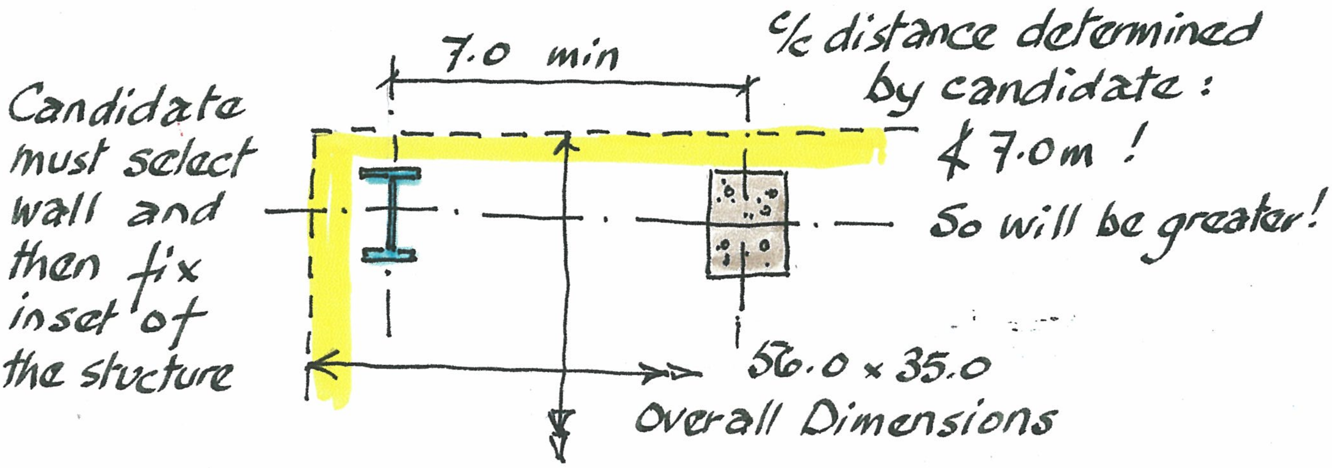
Q5/2009 - Art Gallery

At first reading, the question may give concern: the 56.0m dimension is, of course, eight modules of 7.0m – the minimum centre-to-centre spacing – but then the structure and cladding must overlap the plan dimension at each end! There is no mention of cladding, external walls, doors and windows; and yet they must be there to protect the valuable contents! It is not clear whether Level 1 is at "Datum 0.0m": if it is, then a large portion of the site must be excavated and the surrounding soil supported. Again, the position of the second storey is not prescribed.

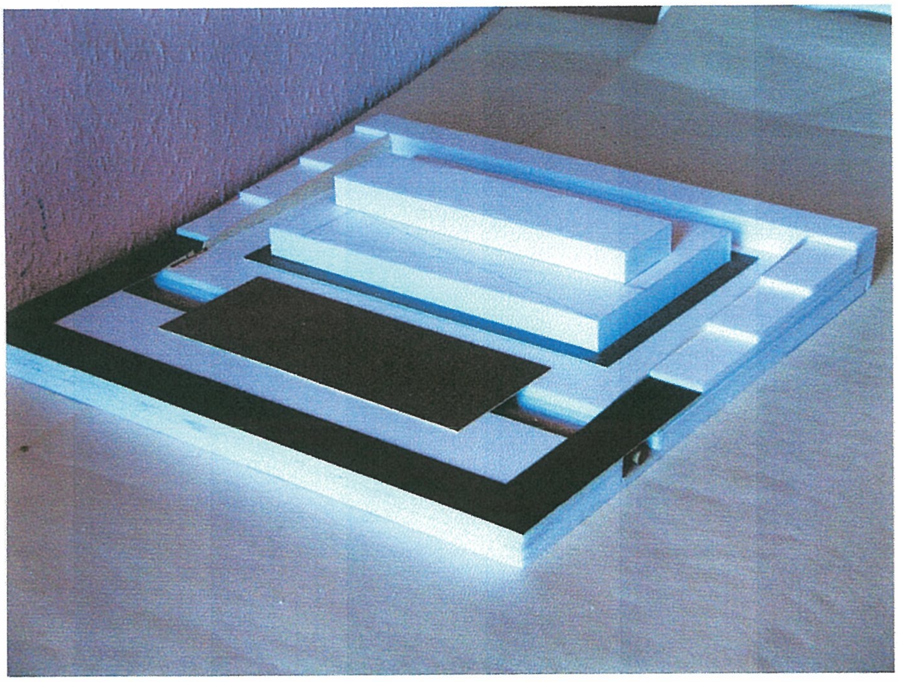
All this "doubt" must not be assumed to be a "mistake" on the part of the Examiner. To do so would be like telling your Client that he is wrong! You must assume that the question is cleverly constructed and contains a wealth of alternatives and design tasks!

Some of these tasks can be listed, conclusions drawn and designs formulated:

- The plan dimensions for Level 1 are 56.0m x 35.0m overall. Appropriate walls and structure must fit within these overall dimensions. The choice of walls and structure are left to the candidate. There will be no windows at Level 1 – for security reasons – hence the daylighting will be through the roofs.

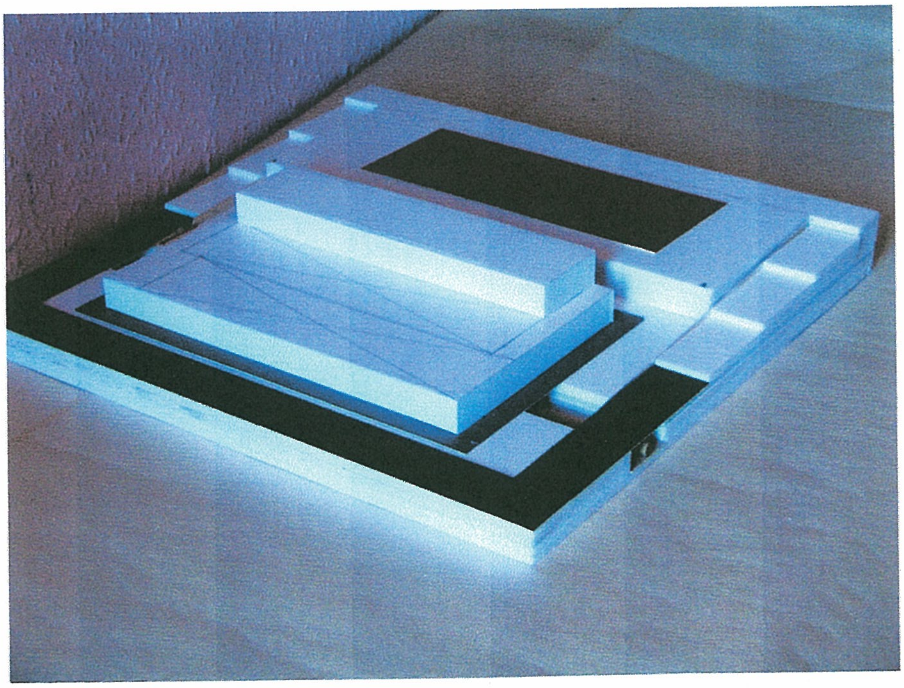


If Level 1 is at Datum then most of the site needs to be excavated and the sides upheld. There does not appear to be sufficient space to form a 1:2 slope at the top of the site.

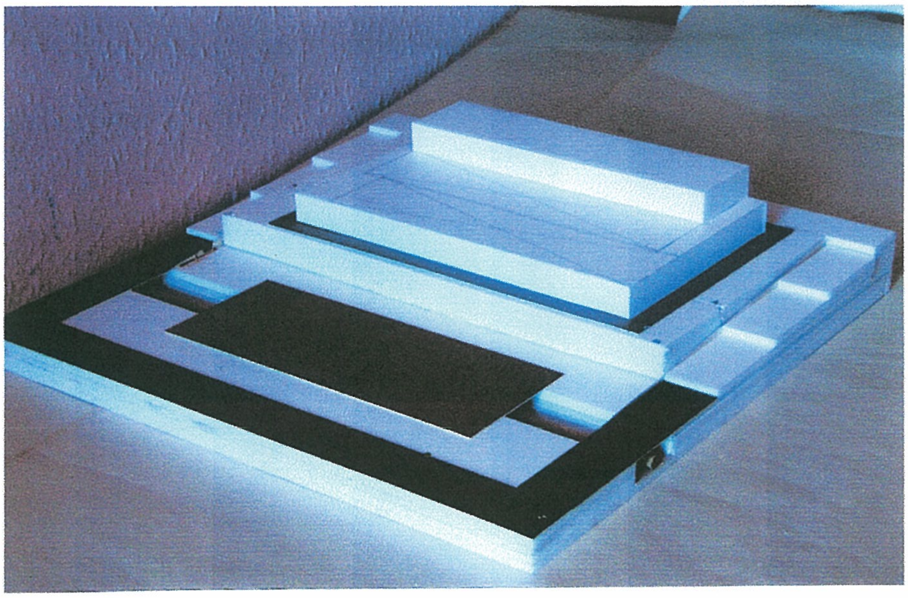


The car-park area staddles the culvert with a suspended slab: access is at the North-West corner. Pedestrian access via a ramp or stairs will be at the South-East corner. (see Client's requirement number 6).

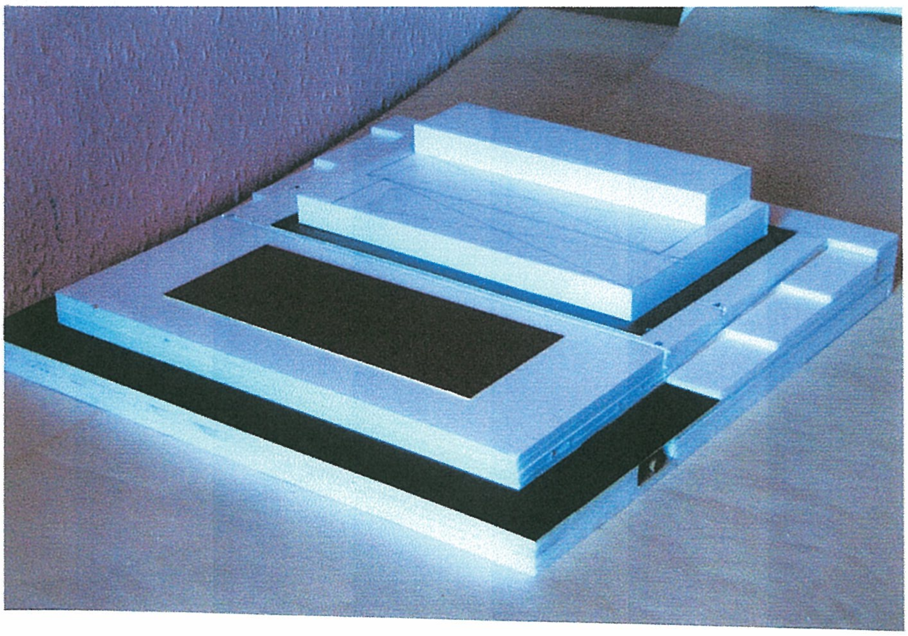
A second option is to excavate part of the site, form a retaining wall across the site and build-up the back of the site.
The car park would be sited here with access from the South-East corner.



The main building would straddle the culvert with a suspended slab: access for pedestrians would be at the North-West corner with a link ramp/stairs from the car park.



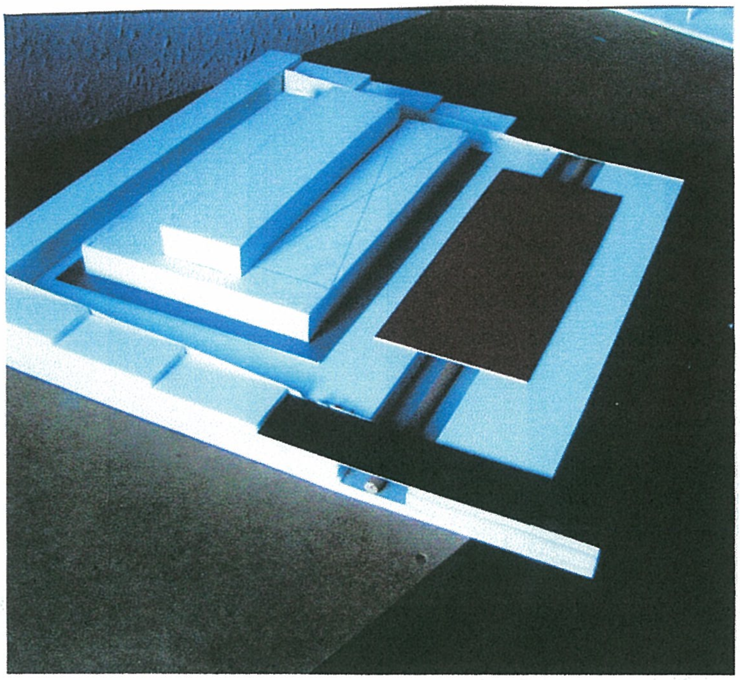
A third option is to build-up the larger part of the sloping site with a retaining wall across the site. There would be no re-usable excavated sandy clay this way and the whole fill would have to be imported. The car park and vehicle access would be as for the first option, with pedestrian access from the South-East corner. Ramp/stair links would be needed at the retaining wall. Windows in the West side of the second storey would be able to look out over the car park.

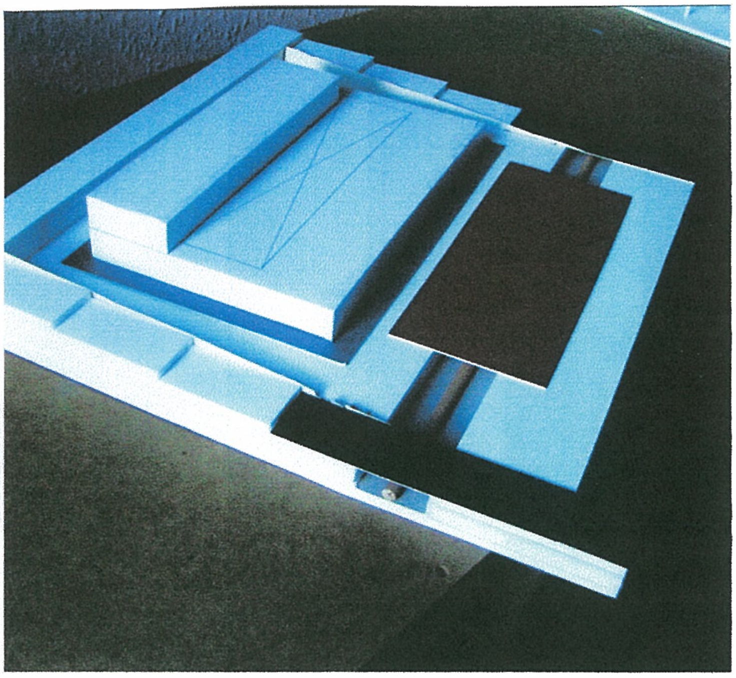


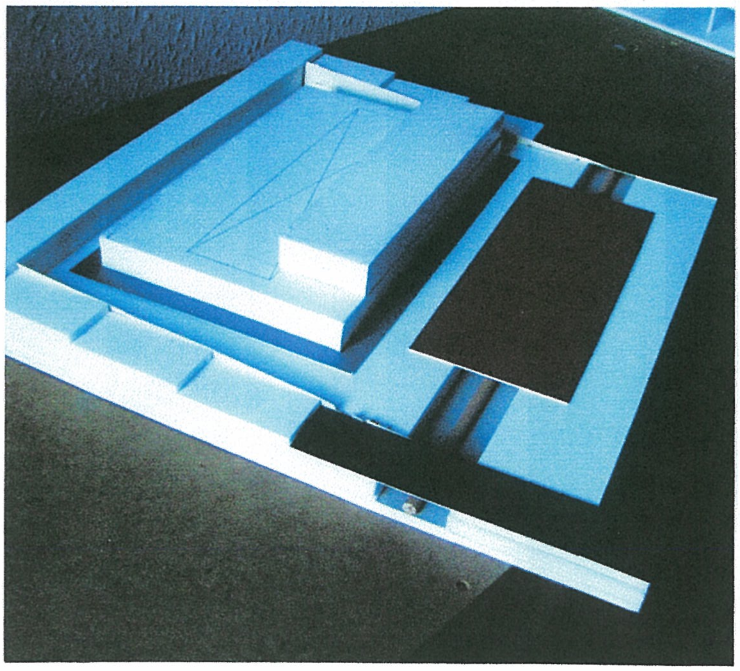
The fourth option considered here is to build-up the whole site with retaining walls on three sides. Again, the whole fill would need to be imported. Vehicle access at the North-West corner would be up a purpose-built ramp. This option would allow a road to be built beside the main building so that emergency vehicles could enter/leave at the South-East corner. Considerable works would be needed to relieve the load on the culvert (see Client's requirement number 7)

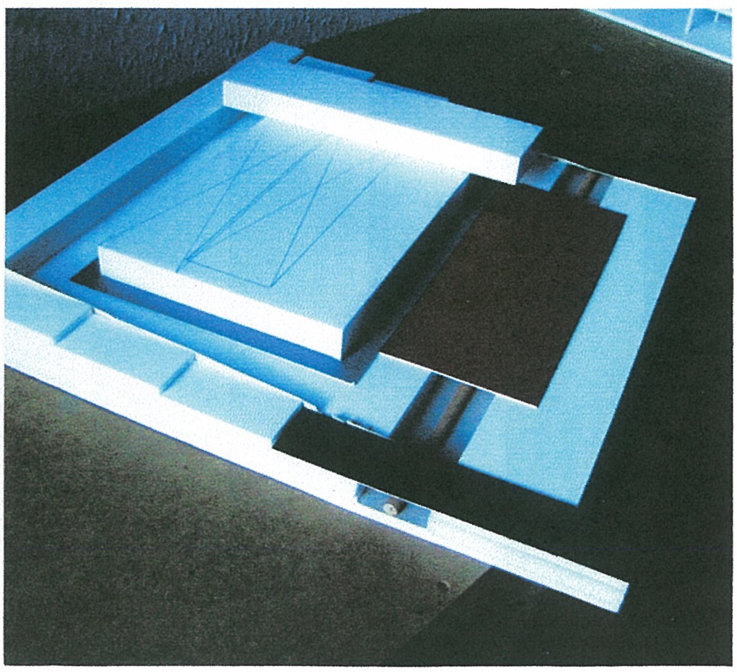
If the candidate offered these options they would need to be complete with at least one building frame, suitable foundations for both site options (one without fill and the other with the building on fill), retaining walls and both vehicle and pedestrian access. This approach would appeal to a candidate with civil-engineering experience.

For the candidate with building experience the challenge might lie in developing two building frames and assume an excavated site as shown at the top of page 2.

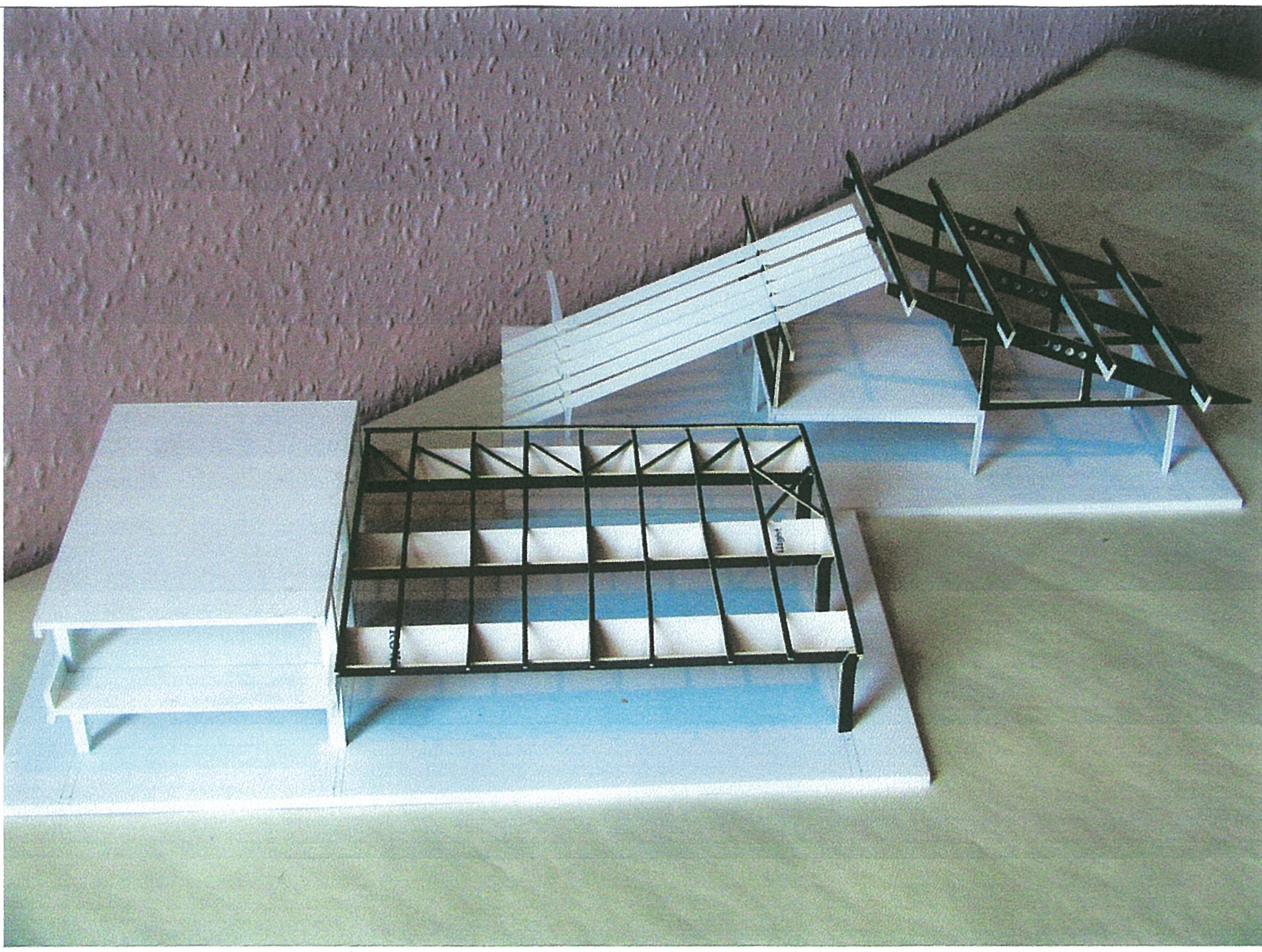








As can be seen (page 4) the position of the second storey (Client's requirements numbers 1, 2 and 3) is the determining feature. My two options have been placed together in the photograph below.



Option 1 has a reinforced-concrete, two-storey building providing the main lateral stability. The main exhibition area is single-storey with roof lighting. The trusses are open web (although solid in the model for practical modeling reasons) and probably welded tubular steel construction.

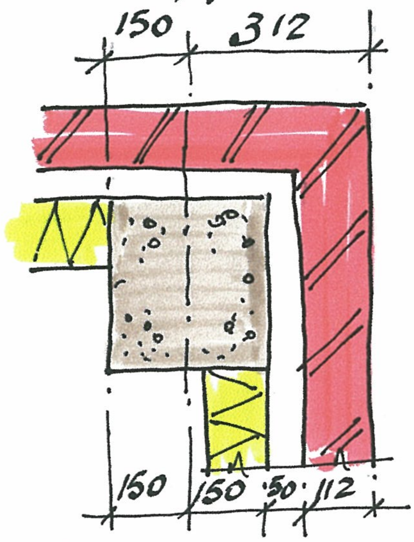
Option 2 has a single-storey, reinforced-concrete "core" to provide support and stability. The model shows two options for the roof. The "basic" one, on the left, has closely-spaced rafters spanning from a portalised, load-bearing wall frame to a similar frame bearing on the edge of the reinforced-concrete "core".

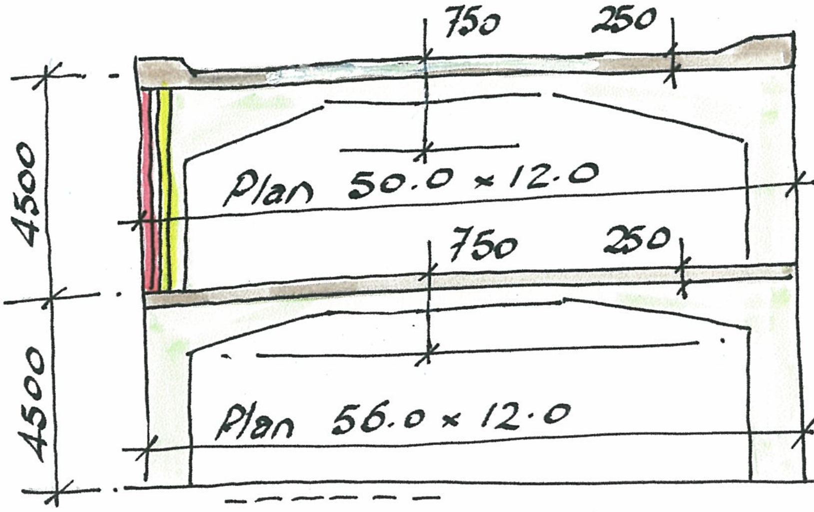
The second roof option, on the right, has fabricated, triangulated rafter "trusses" supporting longitudinal purlins. This would probably be a steel construction, but might be possible in timber using glued-laminated trussing with timber connectors and flitch plates at the joints.

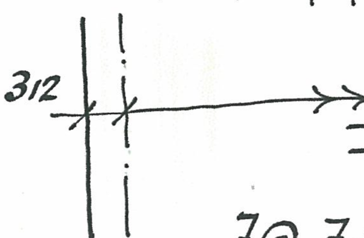
One rather minor point of concern is that the two-storey section is only 50.0m long - 6m shorter than the rest of the building. The first option can accept this but would look a bit truncated unless the second storey were "centred" on the building below. The second option rather needs the ridge to run full length. Perhaps this could be dealt with as a note to the Client suggesting that there would be a benefit if the second storey was as long as the rest of the building?

Although Item 11 omits the detailed design of the stairs and lift shaft, these features should be included on the General Arrangement drawing in Section 2d.

In Option 2, roof glazing would provide the daytime lighting but the central single storey area would probably need supplementary lighting.



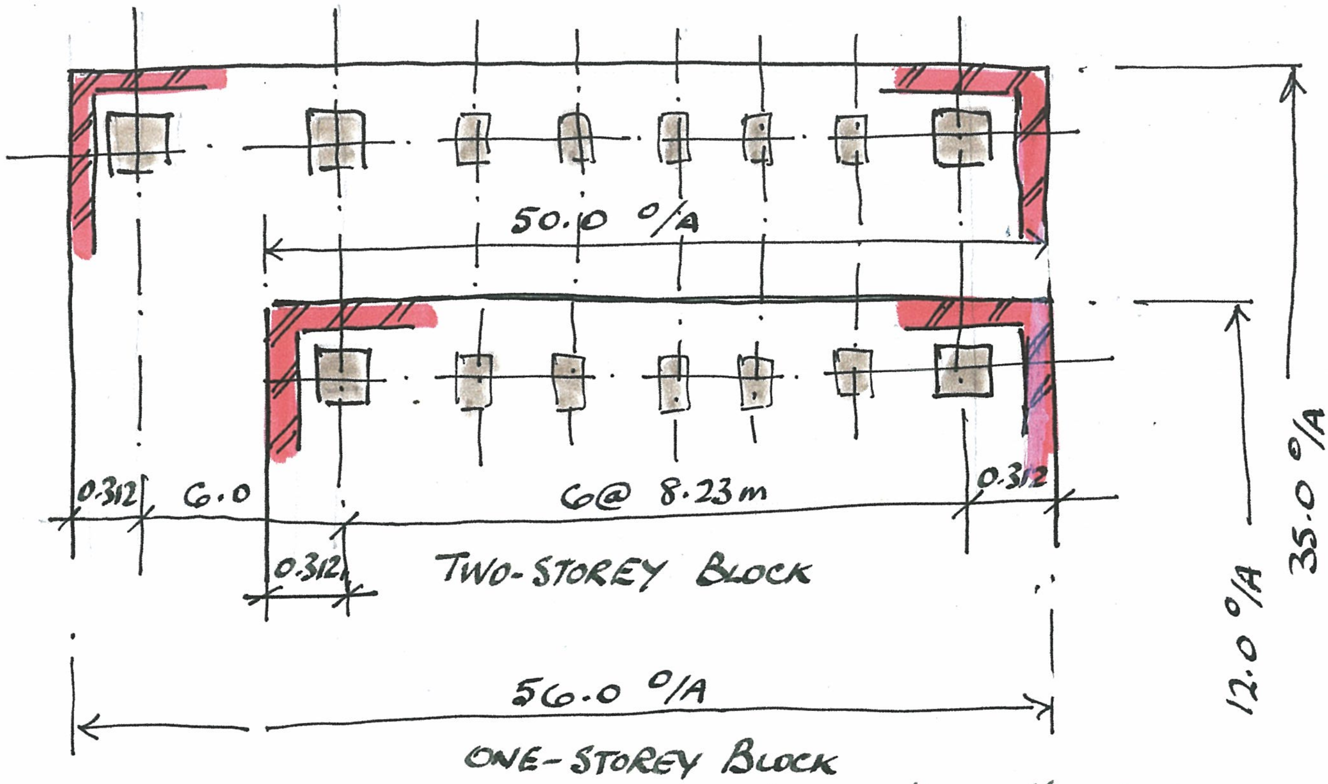




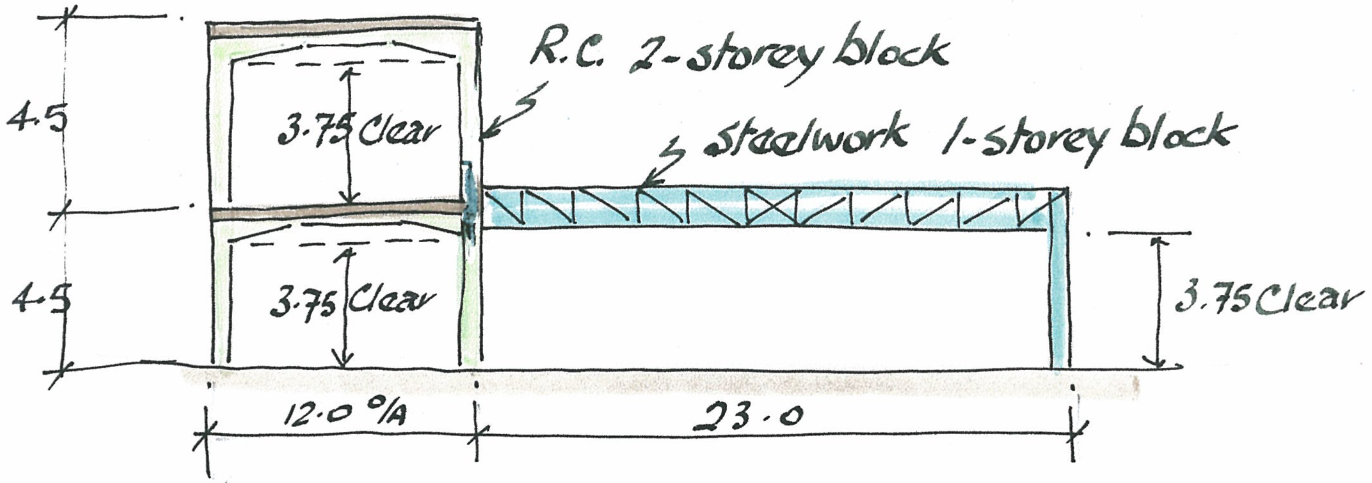
56.0
− 0.625
55.375
7 @ 7.91m. c/c

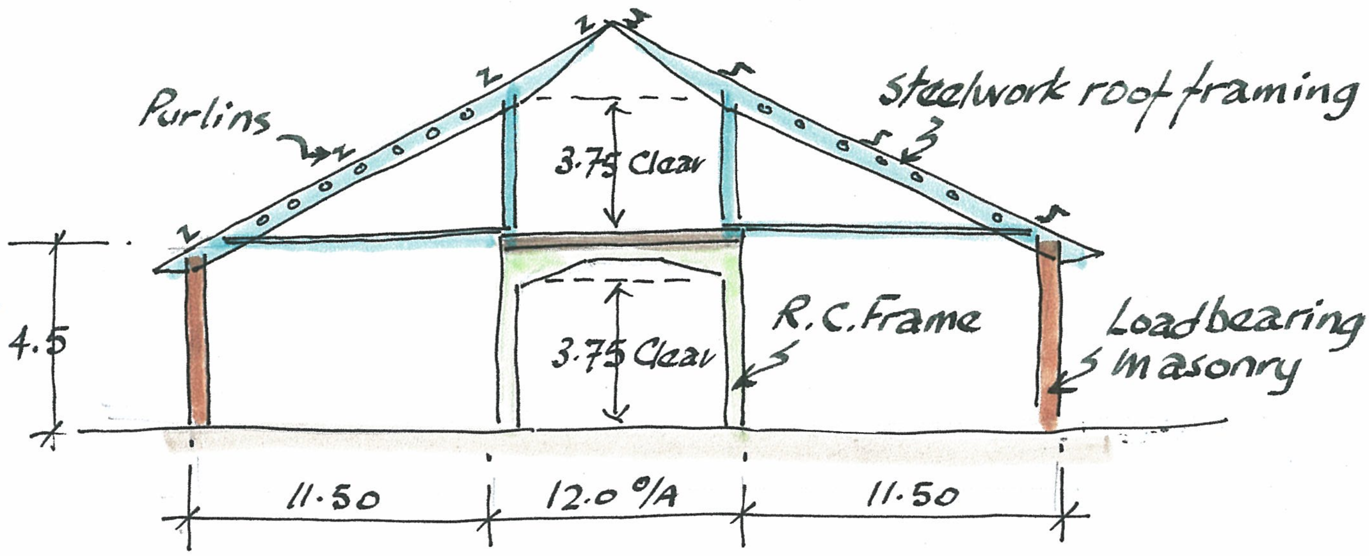
50.0
− 0.625
49.375
6.24 @ 7.91m c/c

RAW

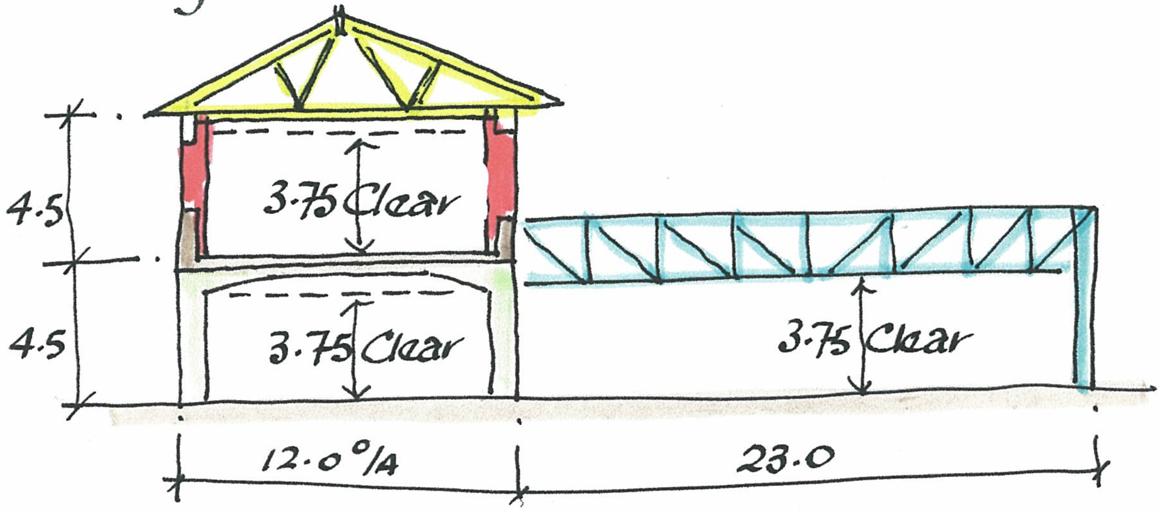


There appears to be an irreconciable disparity between plan dimensions and column centres.



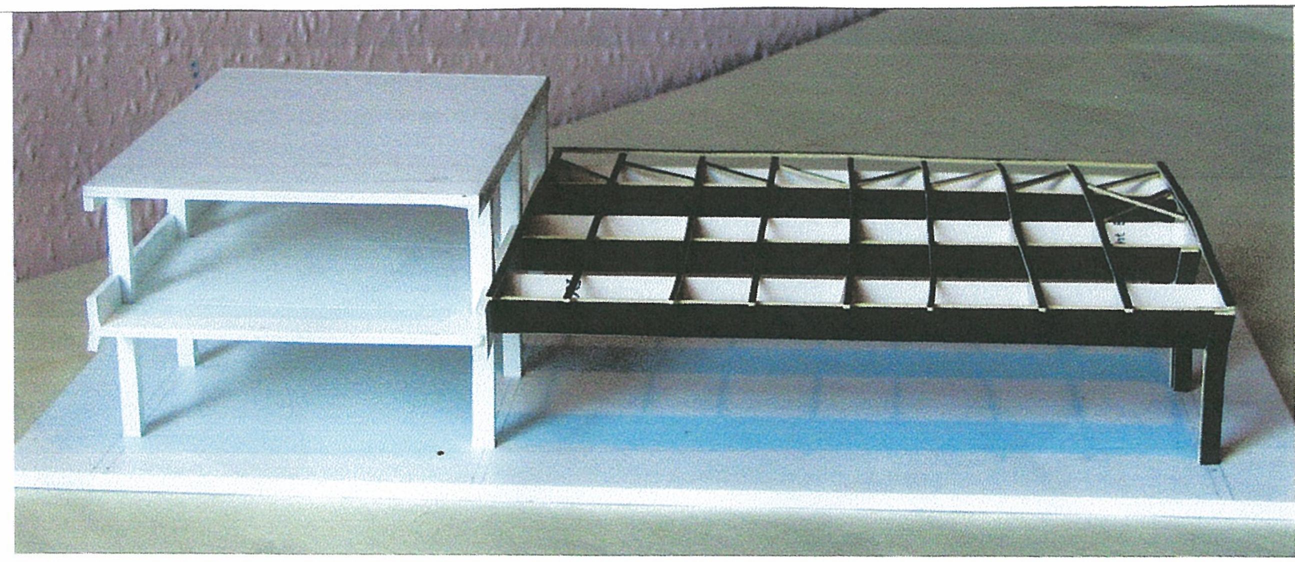


It is clearly desirable to have the upper R.C. portals above the lower R.C. portals. Within the constaints set by the question [Client's requirement number 2] there appears to be an irreconciable disparity between the plan dimensions and column centres. One must question whether the upper storey needs to be a reinfored concrete frame at all. Surely one could support the roof over this part of the complex on traditional loadbearing masonry?

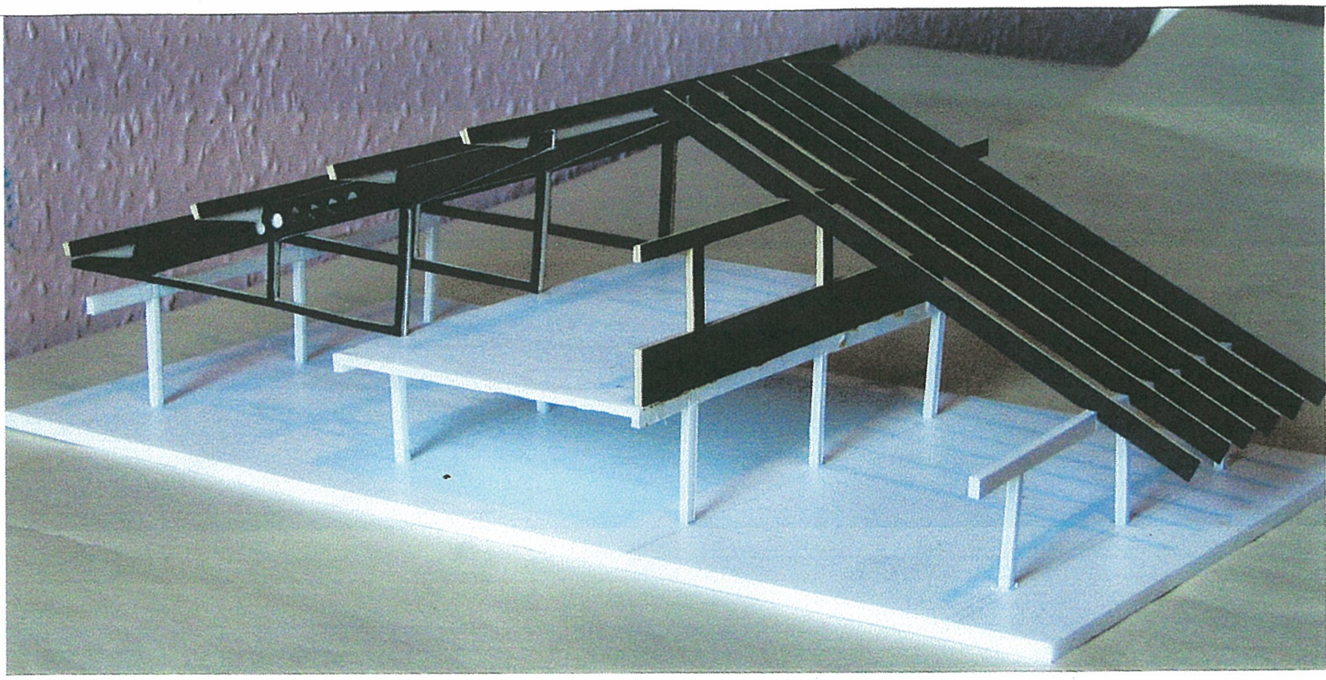


The lower storey columns can be at 7.91m % [which complies], the upper storey enclosing walls and support for the roof can be loadbearing masonry – brick outer skin – cavity insulation – block inner skin – plaster, which also complies. It seems reasonable to have a traditional timber truss – sarking boards – tiles roof.

Note that an International Institution, based in the U.K., should be expected to set its examinations in a manner that expects the "default" answer to be in accordance with U.K. practice and regulations. However, the examination regulations allow the candidate to use any other National Standards and credible, safe practice. The candidate is instructed [urged] to state what assumptions have been made. Consequently, the constuction of walls and roof may be quite different in a different climate: one familiar to the candidate.



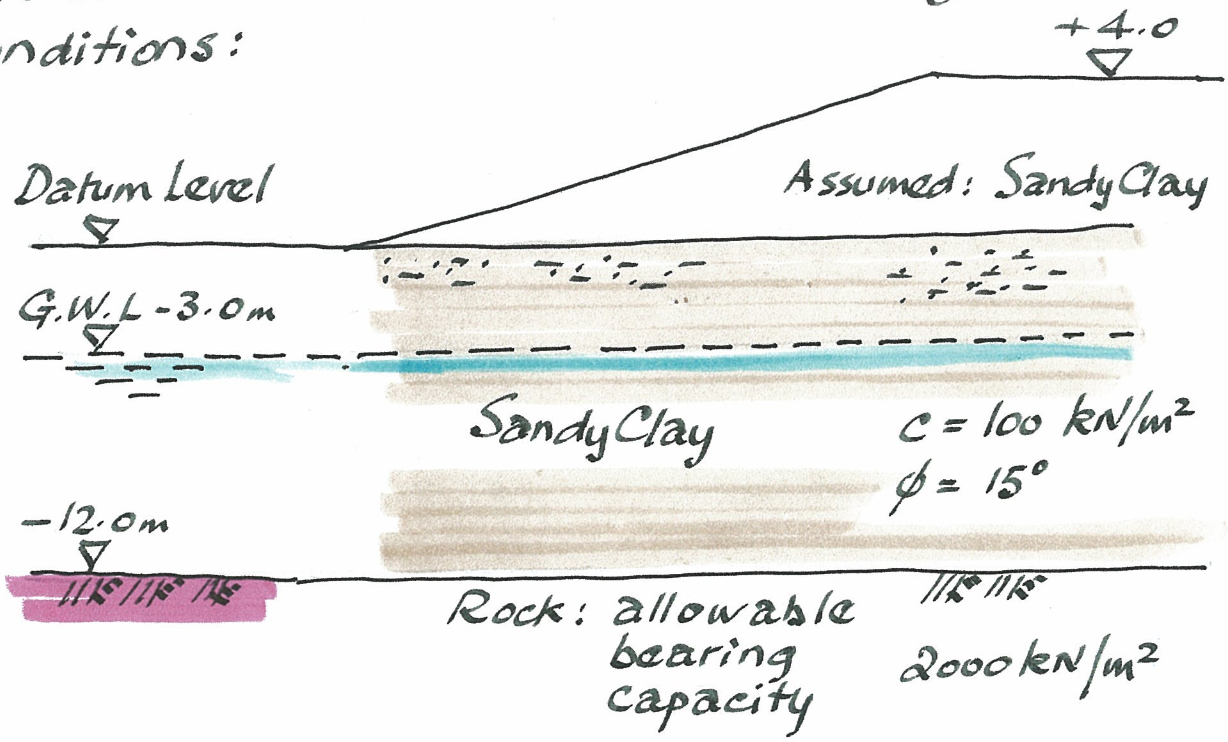
If this option is developed, calculations [Section 2c] will be needed for a typical reinforced concrete panel – slab, beams and column; a typical truss and post: and foundations. These will be translated into drawings [Section 2d] – a GA. plan and section; a typical floor panel [so that a bending schedule can be made and rebar weights measured off]; typical details related to the steelwork such as the connection to the two-storey building: the connections at the head + foot of the post: and the foundations [all three types!]
The Method Statement will feature the insitu construction of the R.C. frame and slabs [falsework; formwork; source, transporting, placing and finishing the concrete]: the fabrication, testing, transporting and erection of the steelwork; and the foundations! The outline construction programme will begin with foundations, proceed to the R.C. frame and finish with the steelwork. The steelwork cannot be erected until the R.C. support is quite ready. Can the trusses be transported in one piece each? If not time will be needed on site to assemble and weld the two halves together.



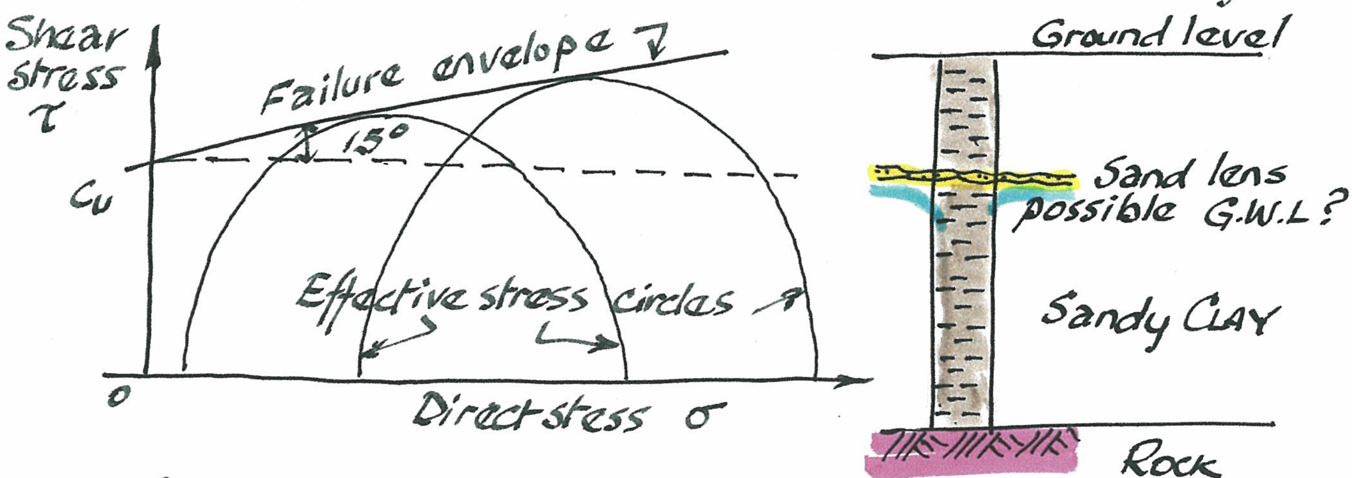
If this option is developed, calculations will be needed [Section 2c] for the reinforced concrete frame and panel - slab, beams and column - and the two external portalised supports: and their foundations! Depending upon which type of roof is chosen, either the triangulated truss and purlins or the rafters and load-bearing wall-frame will need to be "proved". Do not forget the bracing! The drawings [Section 2d] will have a GA. Plan and Section; a typical floor panel and bar schedule: and details of connections as appropriate. Will the purlins need sag rods? How will the wall-frame be prevented from buckling inwards? Do not forget the foundations!

The Method Statement will feature the foundations first and then the R.C. frame and slab [falsework; formwork; source, transporting, placing and finishing the concrete], or will it be precast? Can the triangulated trusses, purlins and/or rafters be transported "full-length"? The programme needs to include foundations, R.C. frame and steelwork, all in sequence.

Site Conditions – Item 10 describes the ground conditions:



With a cohesion value of 100 kN/m² the clay will be "Firm" to "Stiff". The angle of shearing resistance, ϕ = 15°, indicates that the effect of direct stress is minimal; i.e. the sand has little influence on the strength – probably in thin layers or lenses within the clay. This would account for the reported ground-water level which is unusual in a clay soil.



Possibly "some" may be trapped by the suggestion of "sand" and a high G.W.L which would normally halve the bearing capacity, but in this case do not (in my opinion) apply.

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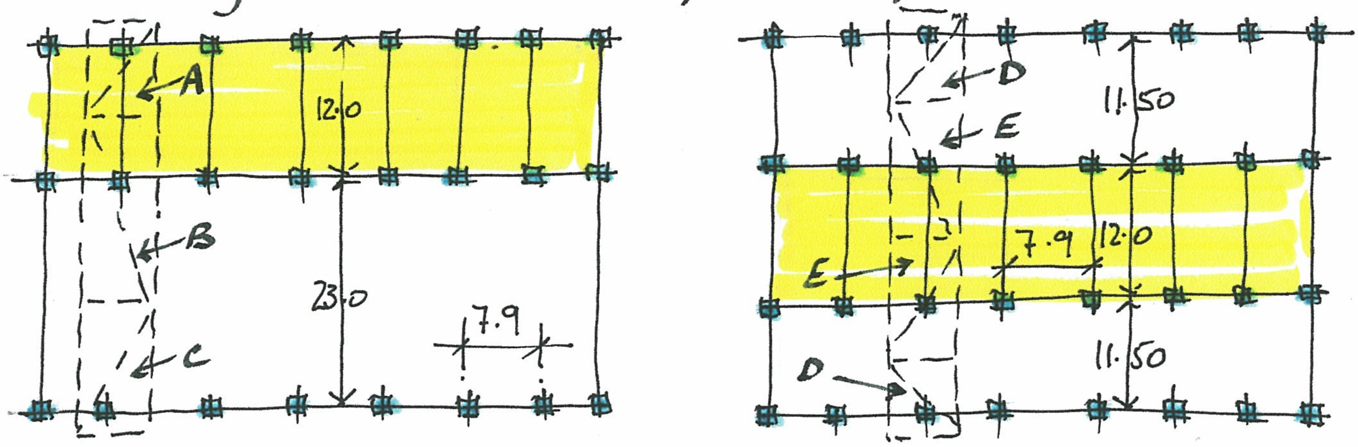
Section 1a requires the candidate to "Prepare ... two distinct and viable solutions ...", so there should be a distinct [different] foundation solution for each Option. You advised not to re-use the Option 1 solution in Option 2. The arrangement is very unlikely to be identical, for example:



And the loading will be different:

$\frac{8.0}{15} = .533 \times 24 = 13.\ kN/m^2$

$2@5.0 + 1@1.5 = 11.5\ kN/m^2$

steel frame (say) $10.0\ kN/m^2$

Very approximately the order (value) of the "pile" or foundation loads is as shown below (kN):

Area A

$3 \times 13 \times (7.9 \times 6.0) = 1850$ kN

$+\ 1 \times 11.5 \times (7.9 \times 6.0) = 545$

2395

Area B

$3 \times 13 \times (7.9 \times 17.5) = 5390$

$+\ 1 \times 11.5 \times (7.9 \times 17.5) = 1590$

6980

Area C

$1 \times 10 \times (7.9 \times 11.5) = 910$

$+\ 1 \times 1.5 \times (7.9 \times 11.5) = 136$

1046

Area D

$1 \times 10 \times (5.75 \times 7.9) = 455$ kN

$1 \times 1.5 \times (5.75 \times 7.9) = 68$

523

Area E

$3 \times 13 \times (7.9 \times 11.75) = 3620$

$1 \times 11.5 \times (7.9 \times 11.75) = 1068$

4688

1 tonne $\simeq$ 10 kN

The calculations on page 12 do not include for the enclosing masonry walls, so an allowance needs to be made.

Cavity wall: $(19.0 \times 0.112) = 2.128$

$+ (20.0 \times 0.150) = 3.0$

$+ (20.0 \times 0.020) = 0.4$

$5.528 \ kN/m^2 \times 4.5 = \underline{\underline{25.0 \ kN/m}}$

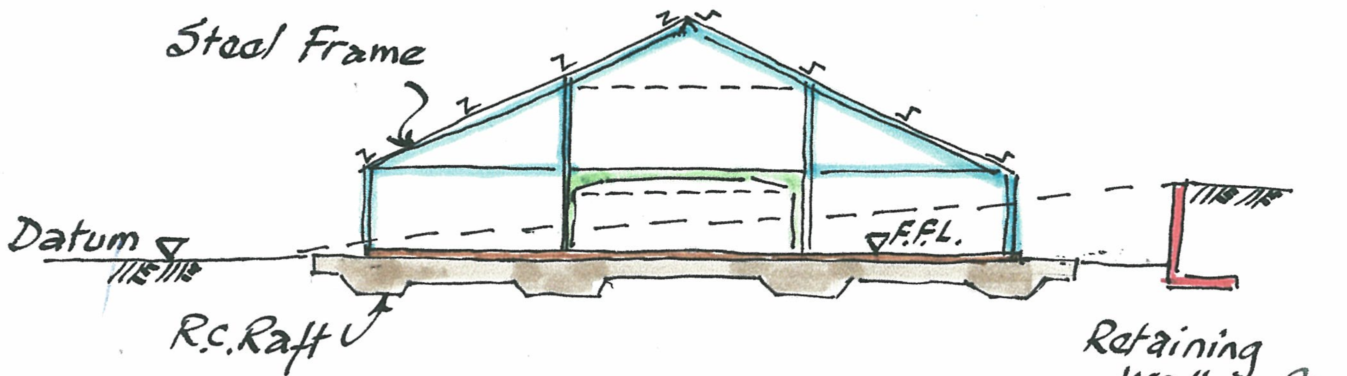
Typical panel/Col $= 25.0 \times 7.9 = \underline{\underline{198 \ kN}}$

Area A	2395 + 2×198	= 2791 kN.	
Area B	6980 + 2×198	= 7376 kN	This should be about right!
Area C	1046 + 198	= 1244 kN	
Area D	523 + 198	= 721 kN	
Area E	4688 + 2×198	= 5084 kN	

The choices for foundations are probably:

Option 1 – with the larger loads under the 2-storey block – steel H-piling driven to rock or CFA bored piling to rock

Option 2 – with lighter, more spread loading – reinforced-concrete raft at Level 1 which extends to include the 3.0m-wide perimeter access [Client's requirement number 4].



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RAW

Total raft area = 62.0 * 41.0 = 248 m^2

All-up load - Option 2 = 2[721 + 5084] = 11610 kN.

Contact pressure under raft = $11610/248$ = 47 kN/m^2

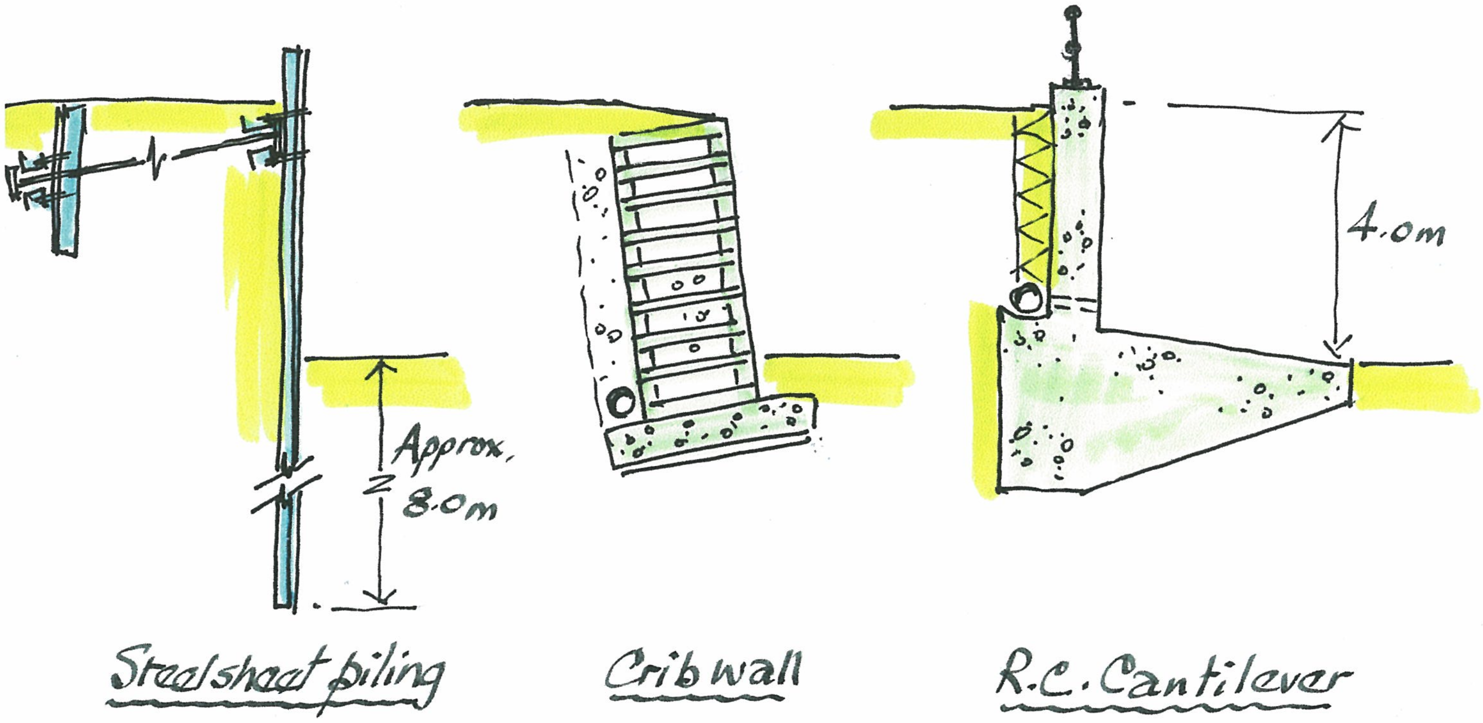
* Spread footing on clay: $q_{allowable}$ = 2 × C_u = 2 × 100 kN/m^2

= 200 > 47

∴ satisfactory.

* Fiona Cobb, "Structural Engineers Pocket Book".

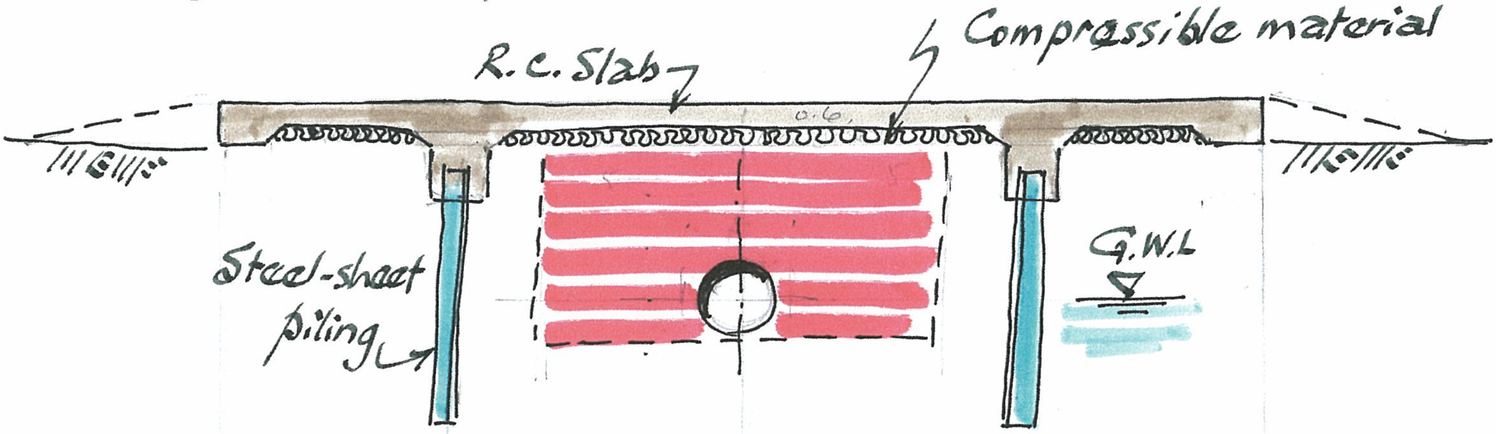
Again, there should be two options for the retaining wall. Distinctness is still required:

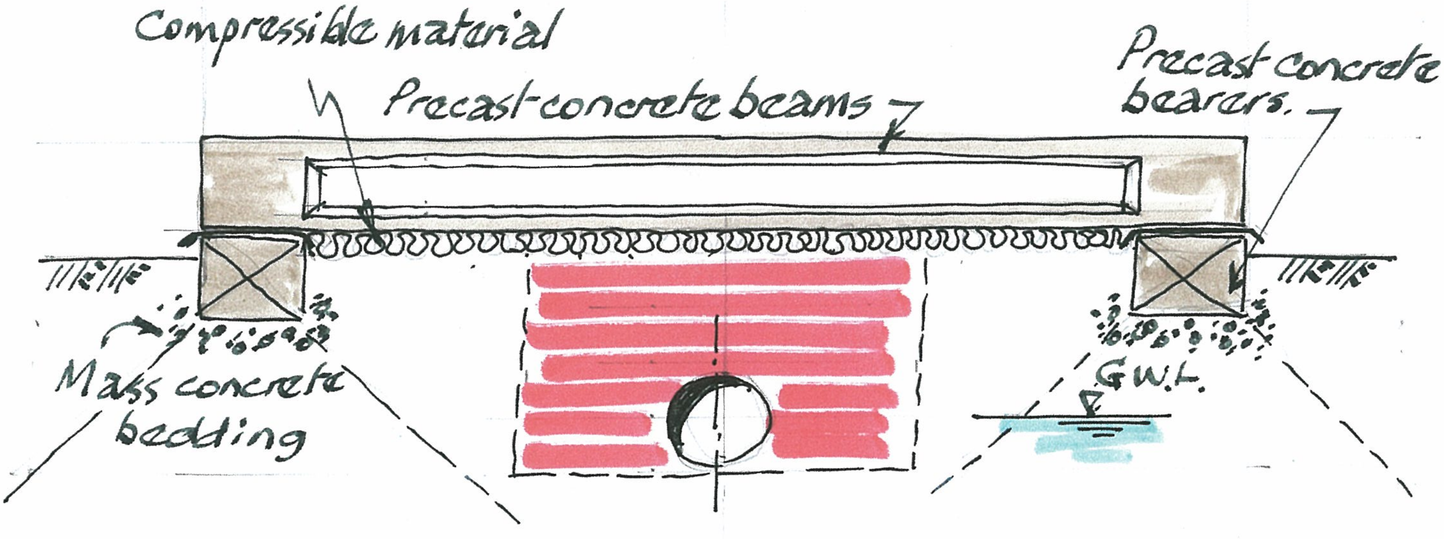


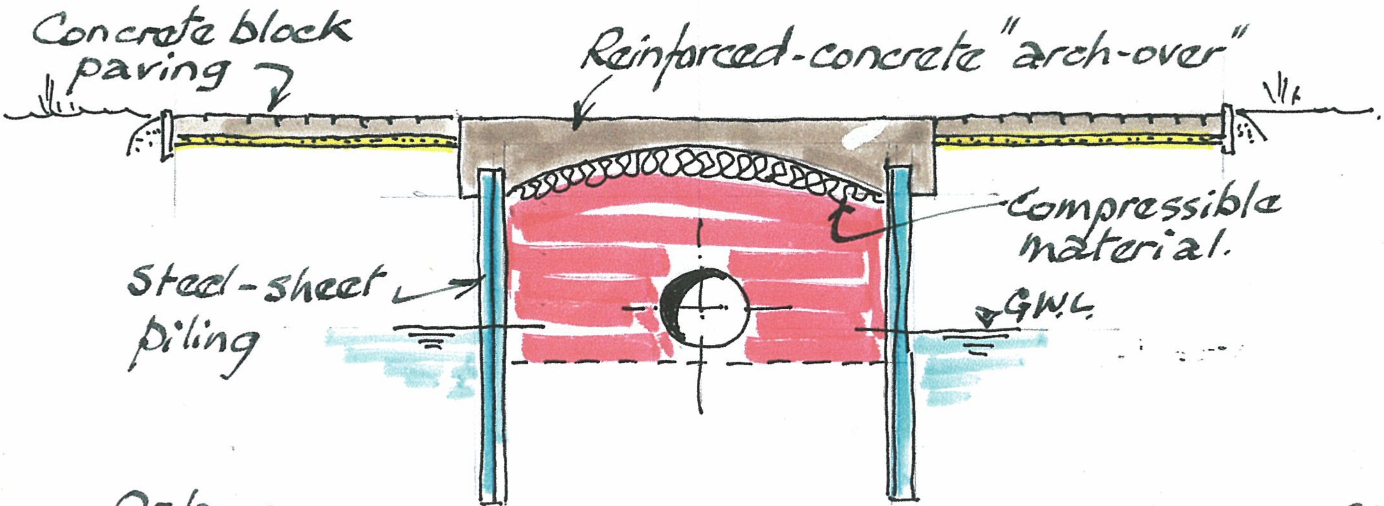
Appropriate calculations would be done in Section 2e. Appropriate sections would be shown in Section 2d. The Method Statement [Section 2e] would explain how the wall would be built. The outline programme would determine a duration and insert this into the sequence of the works – probably: bulk excavation, retaining wall and backfill. This would provide a safe site for the main works.

Although much of the bulk excavation could be reached through the South-Eastern access, it is unlikely that the rest of the work could be done without using the North-Western access and crossing the buried culvert [the retaining wall will provide a "step" in the site profile]. Later, access to the car park will require to cross the culvert too.

Again, two options are required!







Q5/2009

RAW

The permanent access surfaces could be laid in "blacktop", concrete [in which case "air-entrained", frost resistant concrete should be specified], or concrete block paving. The colours of the concrete block paving can be used to mark-out parking bays, etc.

In Section 1b the Client wishes to double-up the parking area [20.0m x 50.0m]. One way would be to pave the required area [200 m²] by judicious use of the excavated site. However, the dimensions of the additional area suggest that the Client is thinking of a second parking area suspended above the original area. This proposal would need access ramps and edge protection as well as drainage. Ref. to: I.Struct.E. Report, "Design recommendations...car parks".