Possible solution to past CM examination question

Question 5 - April 2009

Art Gallery

by Bob Wilson

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 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)**

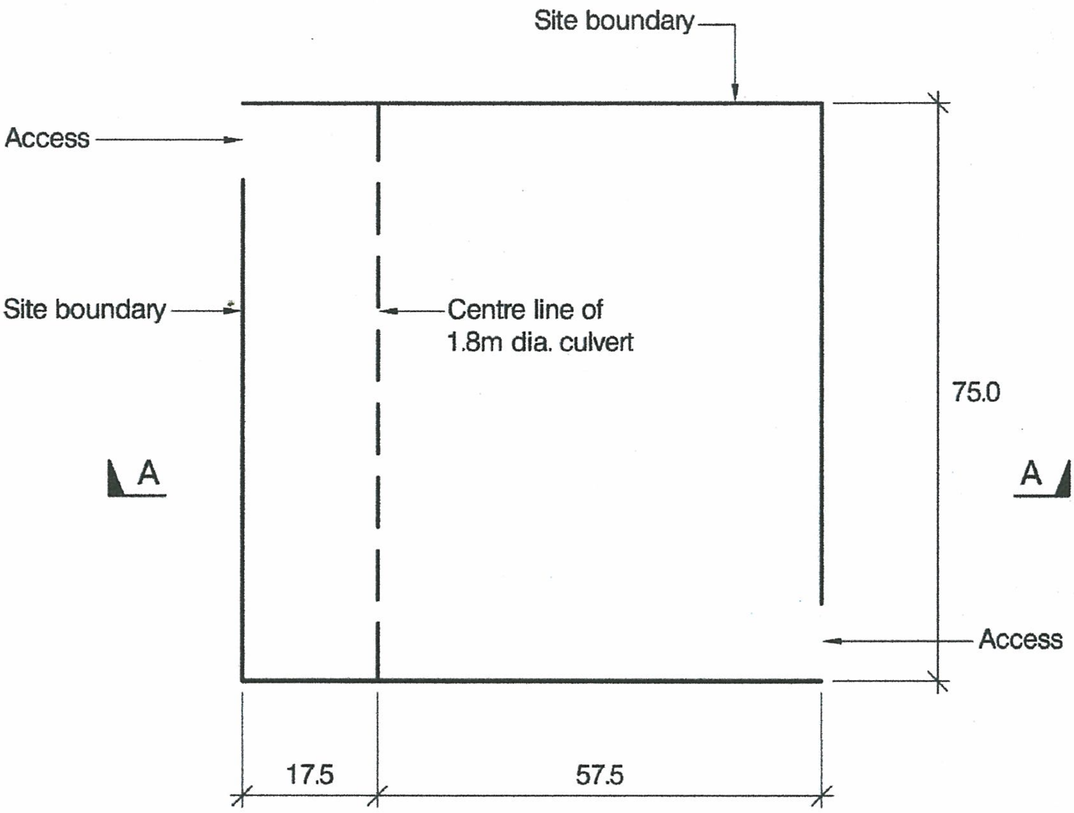
SECTION 2 (50 marks)

For the solution recommended in Section 1(a):

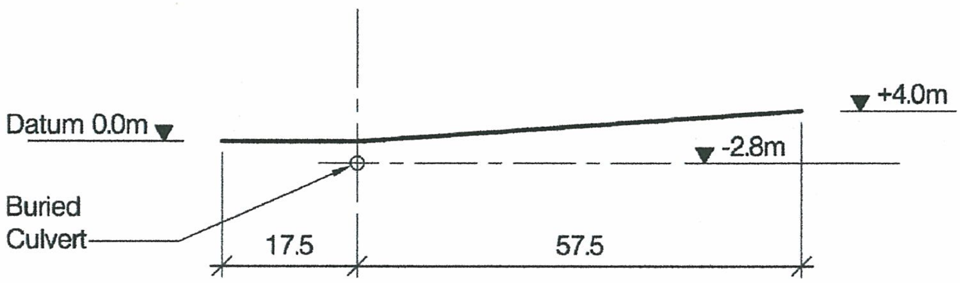
c. Prepare sufficient design calculations to establish the form and size of all the principal structural elements including foundations, any structure associated with the car park and any significant retaining structures. **(20 marks)**

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

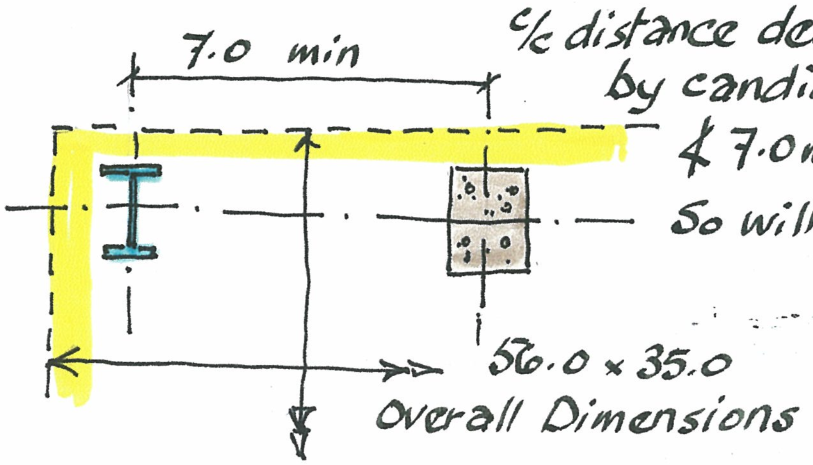
At first reading, the question may give concern: the 56.0m dimension is, of course, eight modules of 7.0m – the minimum centre-to-centre spacing – but then the structure and cladding must overlap the plan dimension at each end! There is no mention of cladding, external walls, doors and windows; and yet 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 <u>not</u> 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:

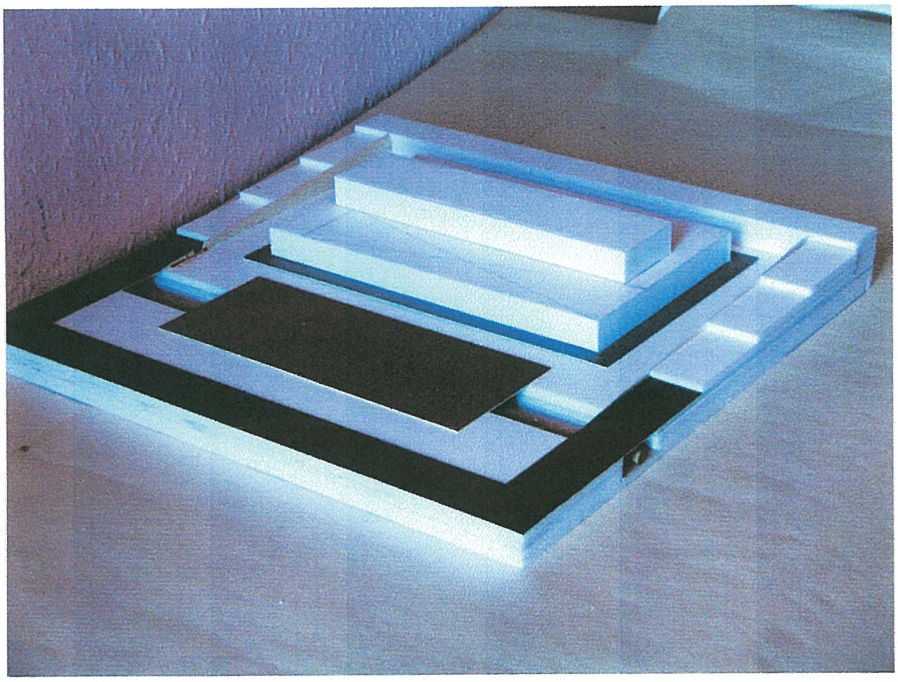
- The plan dimensions for Level 1 are 56.0m x 35.0m <u>overall</u>. Appropriate walls and structure must fit within these overall dimensions. The choice of walls and structure are left to the candidate. There will be no windows at Level 1 – for security reasons – hence the daylighting will be through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

Candidate must select wall and then fix inset of the structure



c/c distance determined by candidate: ≮ 7.0m! So will be greater!

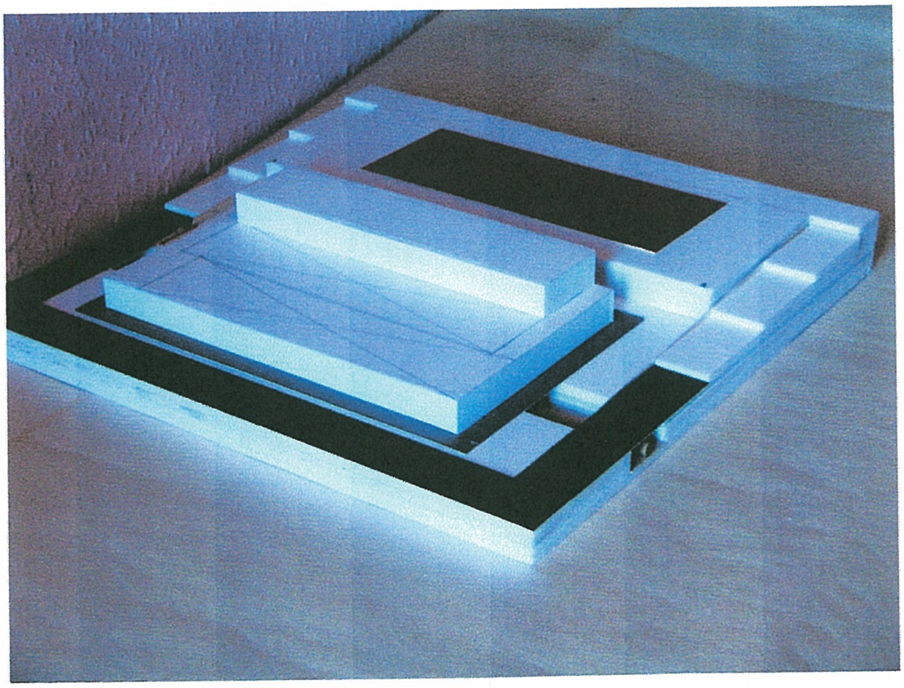
If Level 1 is at Datum then most of the site needs to be excavated and the sides upheld. There does not appear to be sufficient space to form a 1:2 slope at the top of the site.



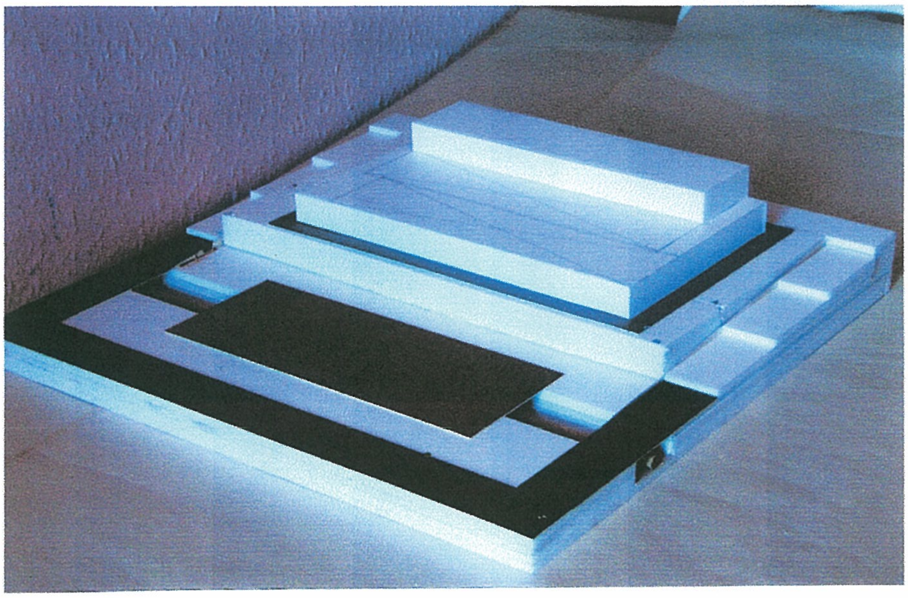
The car-park area staddles the culvert with a suspended slab: access is at the North-West corner. Pedestrian access via a ramp or stairs will be at the South-East corner. (see Client's requirement number 6).

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.

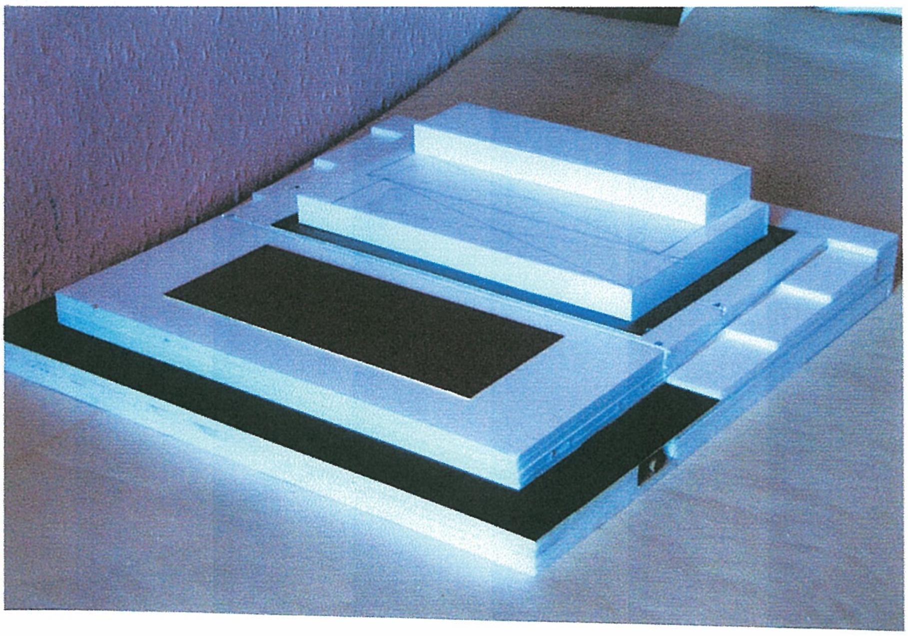
The car park would be sited here with access from the South-East corner.



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.



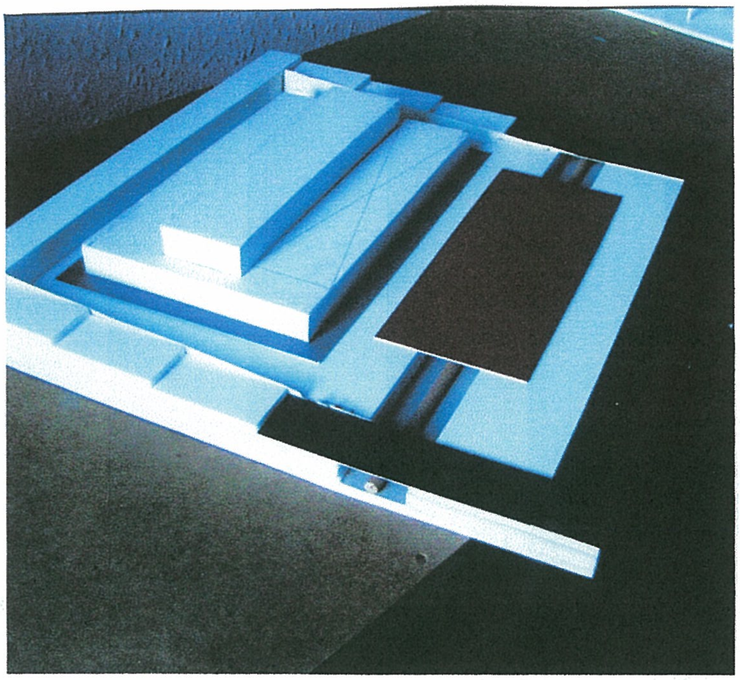
A third option is to build-up the larger part of the sloping site with a retaining wall across the site. There would be no re-usable excavated sandy clay this way and the whole fill would have to be imported. The car park and vehicle access would be as for the first option, with pedestrian access from 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.

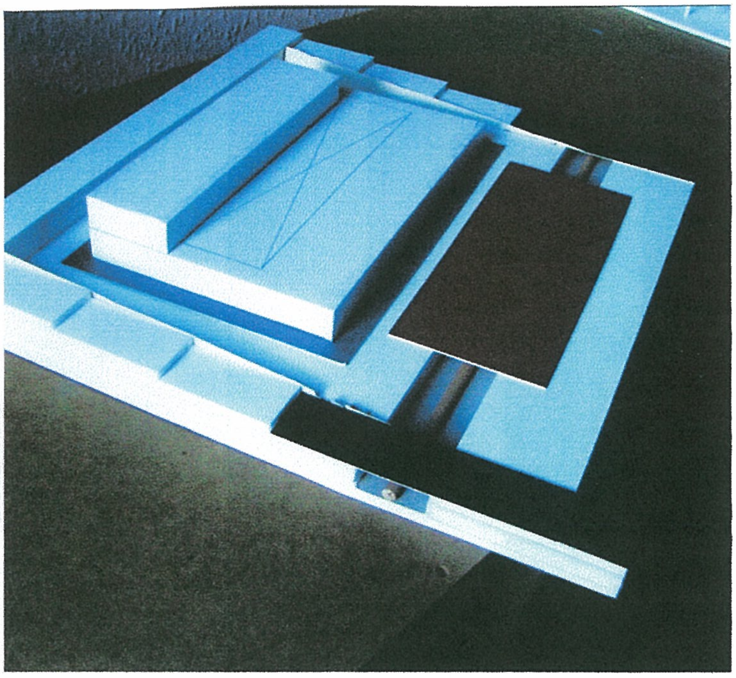


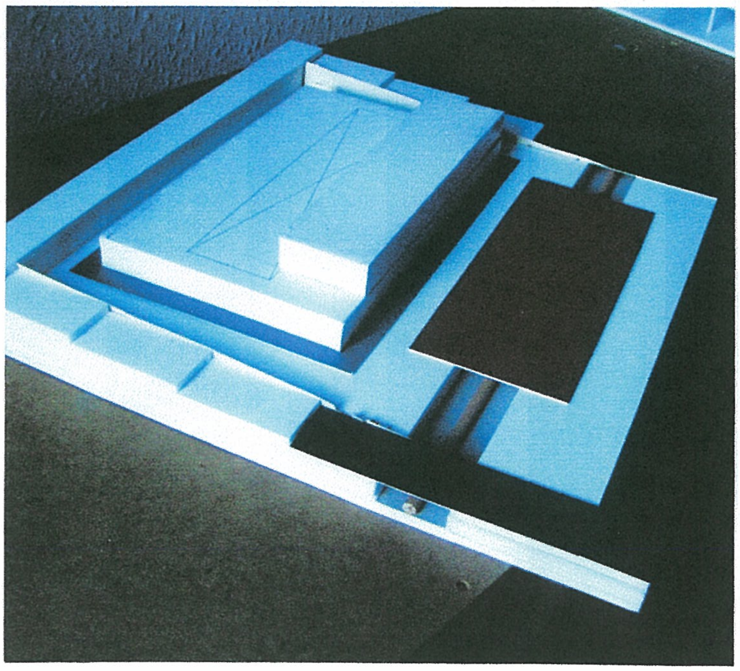
The fourth option considered here is to build-up the whole site with retaining walls on three sides. Again, the whole fill would need to be imported. Vehicle access at the North-West corner would be up a purpose-built ramp. This option would allow a road to be built beside the main building so that emergency 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)

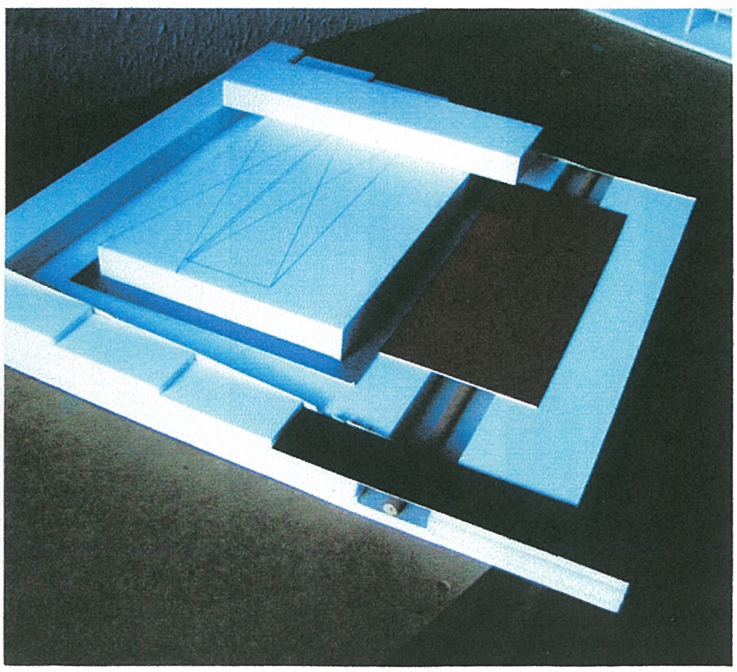
If the candidate offered these options they would need to be complete with at least one building frame, suitable foundations for both site options (one without fill and the other with the building on fill), retaining walls and both vehicle and pedestrian access. This approach would appeal to a candidate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

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

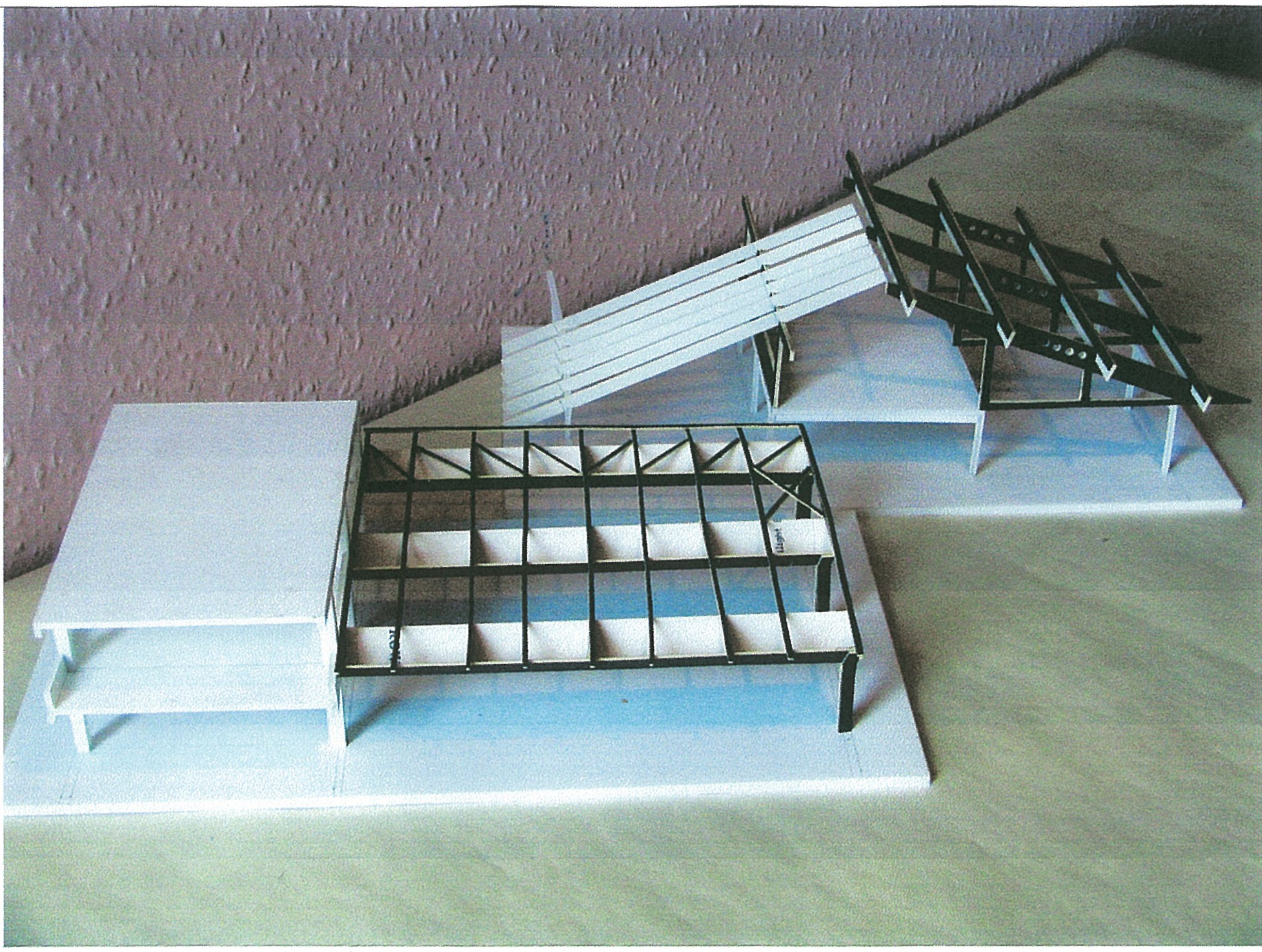








As can be seen (page 4) the position of the second storey (Client's requirements numbers 1, 2 and 3) is the determining feature. My two options have been placed together in the photograph below.



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.

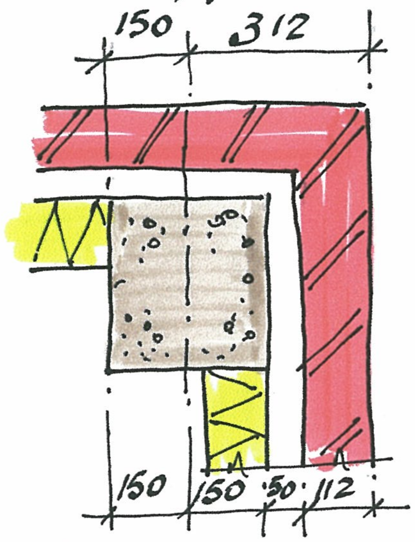
Option 2 has a single-storey, reinforced-concrete "core" to provide support and stability. The model shows two options for the roof. The "basic" one, on the left, has closely-spaced rafters spanning from a portalised, load-bearing wall frame to a similar frame bearing on the edge of the reinforced-concrete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

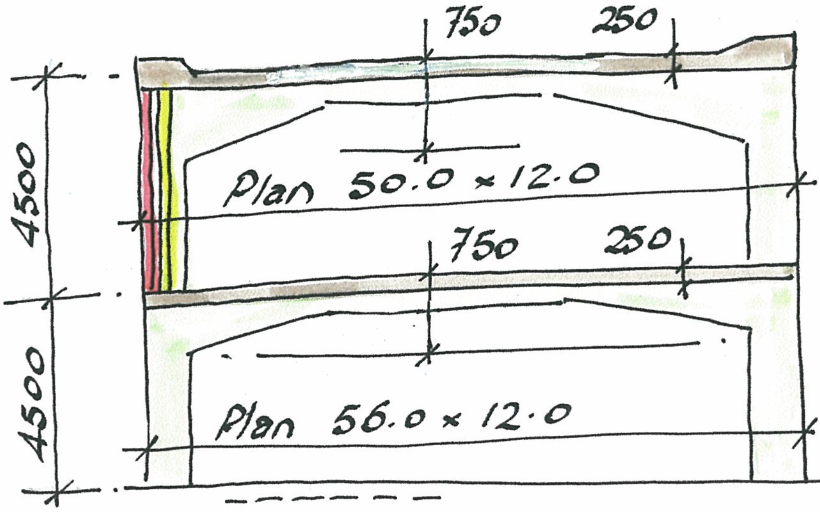
The second roof option, on the right, has fabricated, triangulated rafter "trusses" supporting longitudinal purlins. This would probably be a steel construction, but might be possible in timber using glued-laminated trussing with timber connectors and flitch plates at the joints.

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.

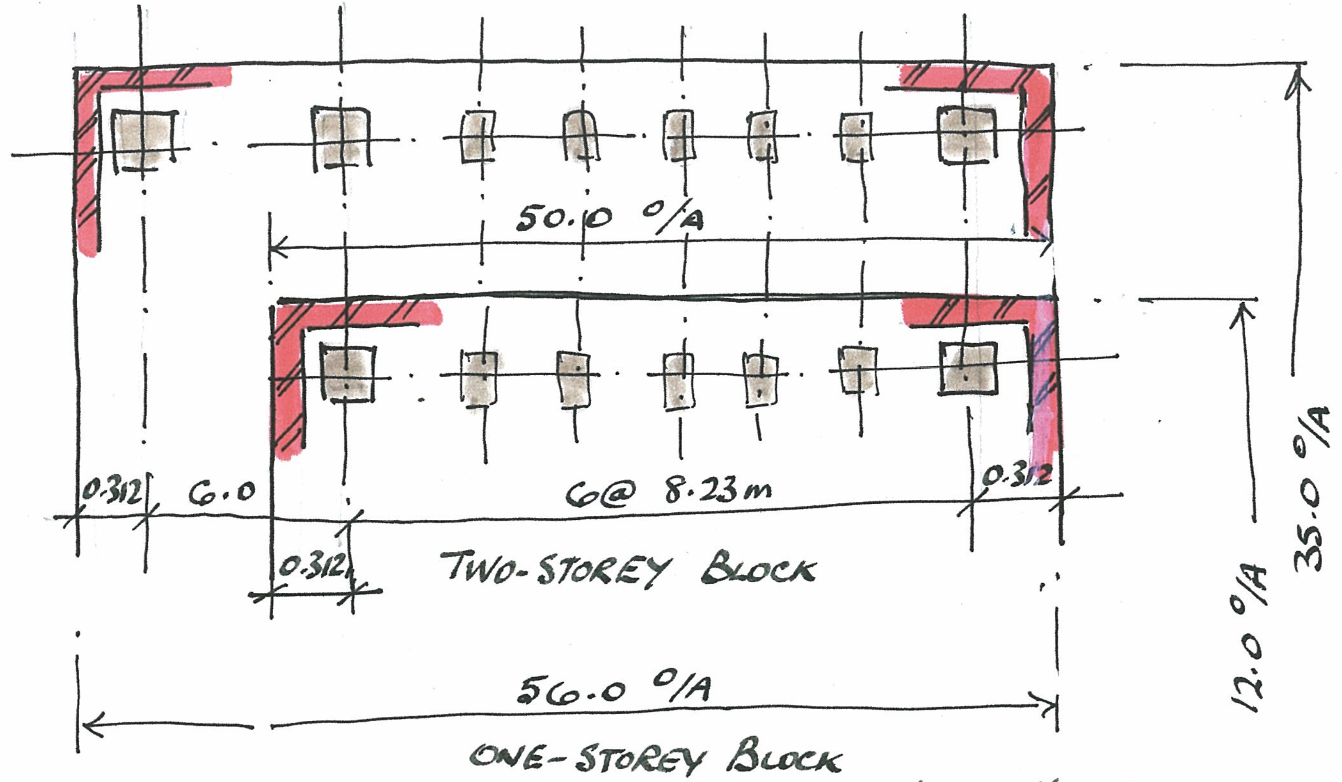




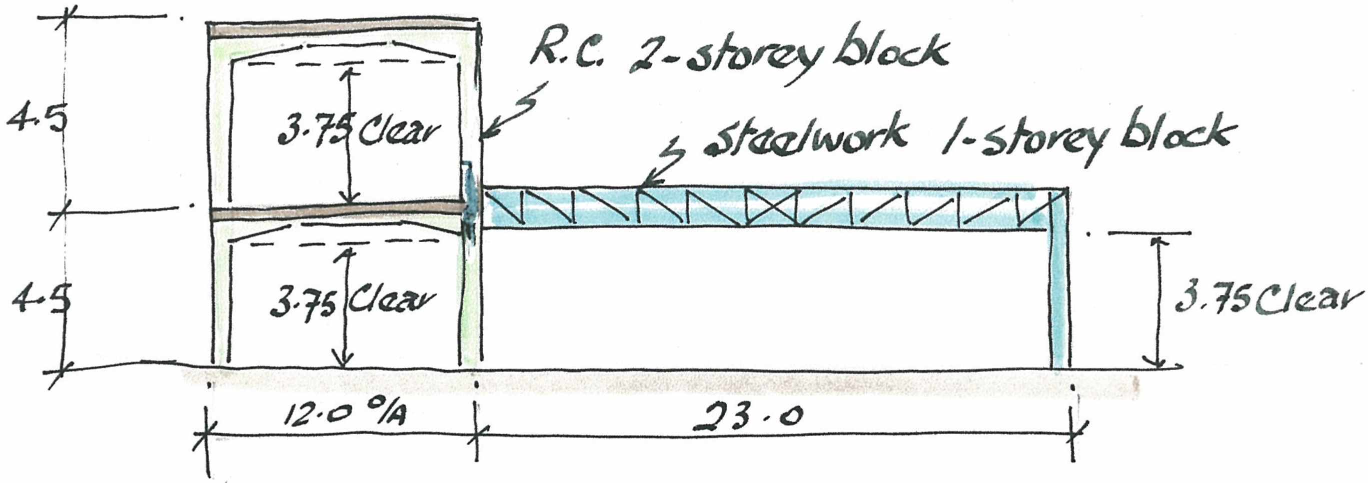
312

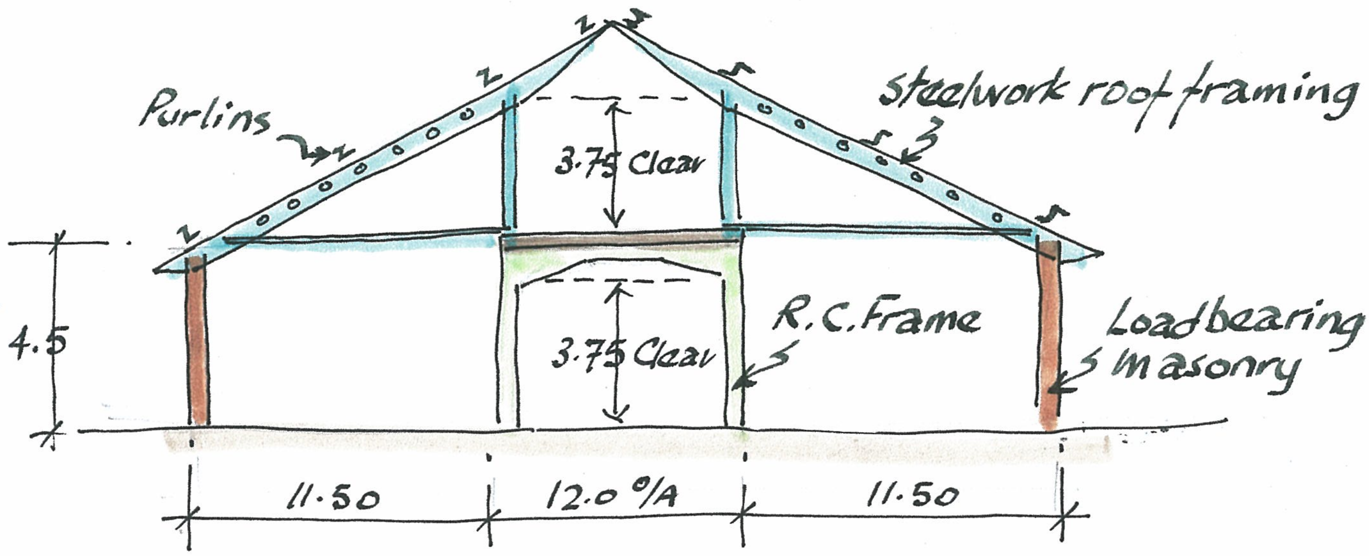
56.0	50.0
− 0.625	− 0.625
55.375	49.375
7 @ 7.91m c/c	6.24 @ 7.91m c/c

RAW

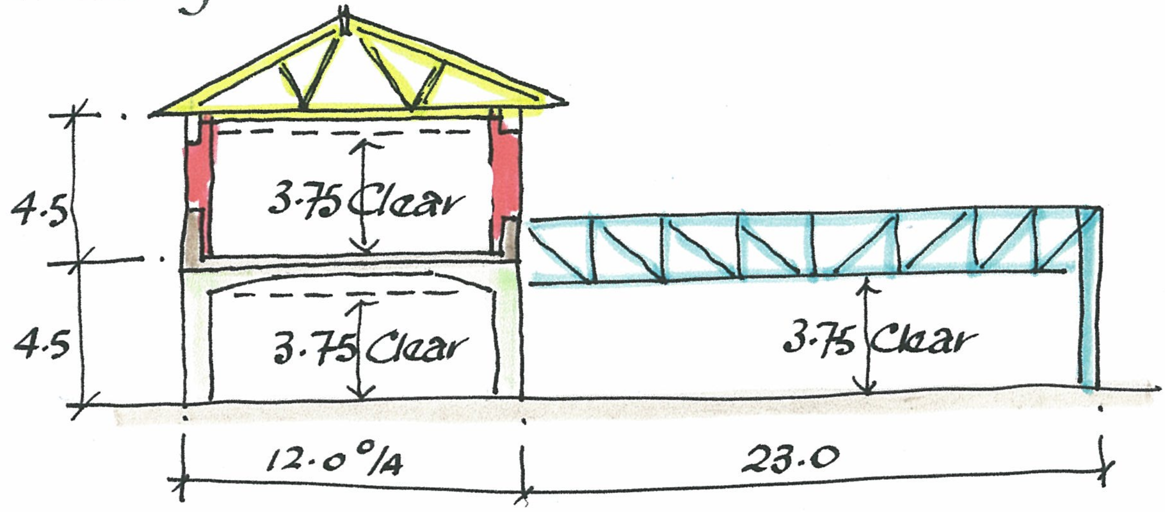


There appears to be an irreconciable disparity between plan dimensions and column centres.



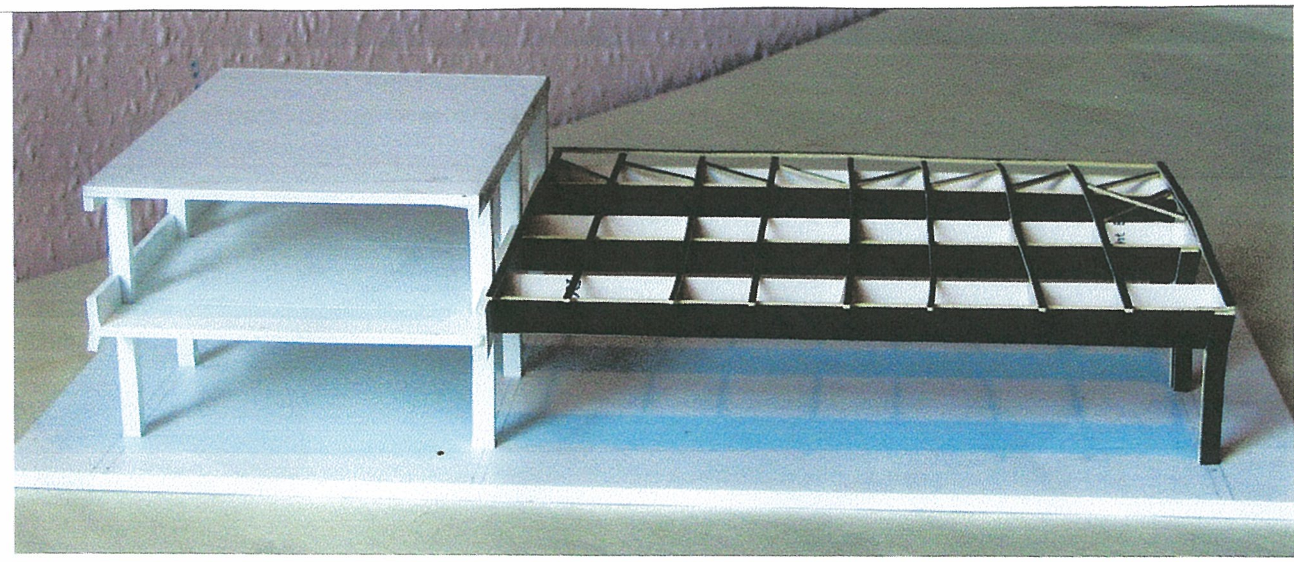


It is clearly desirable to have the upper R.C. portals above the lower R.C. portals. Within the constaints set by the question [Client's requirement number 2] there appears to be an irreconciable disparity between the plan dimensions and column centres. One must question whether the upper storey needs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

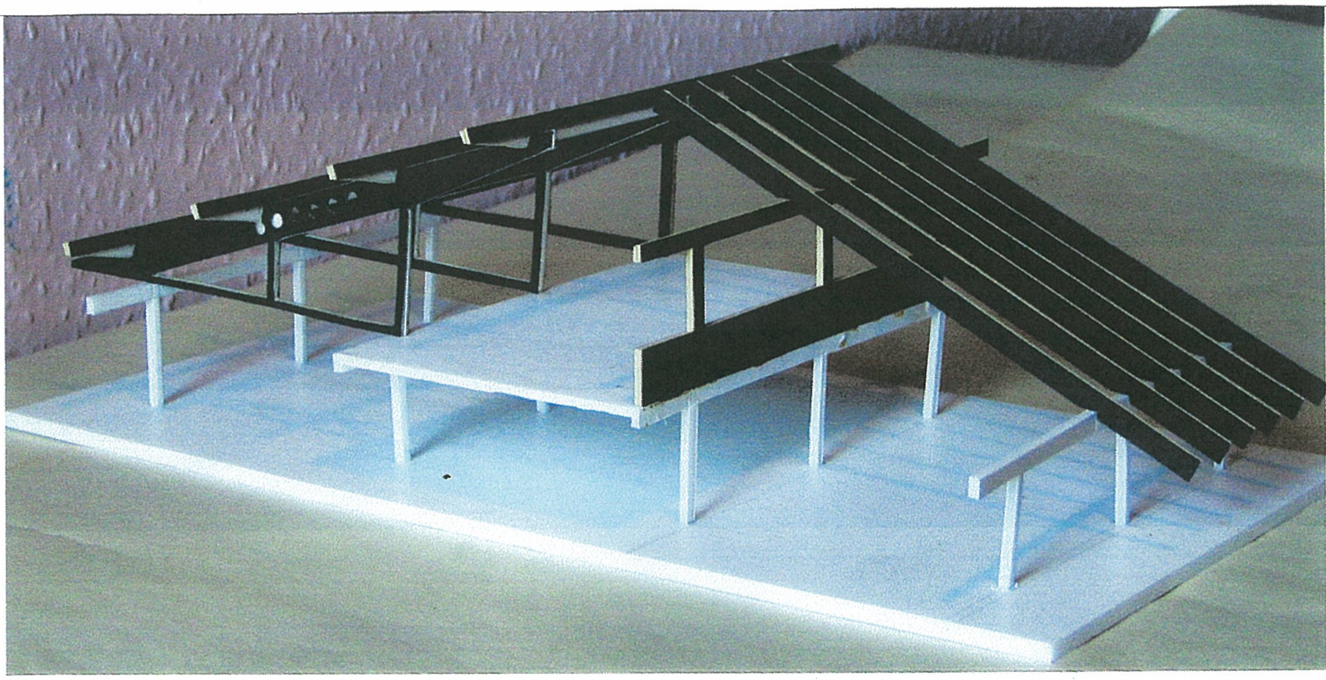


The lower storey columns can be at 7.91m % [which complies], the upper storey enclosing walls and support for the roof can be loadbearing masonry - brick outer skin - cavity insulation - block inner skin - plaster, which also complies. It seems reasonable to have a traditional timber truss - sarking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



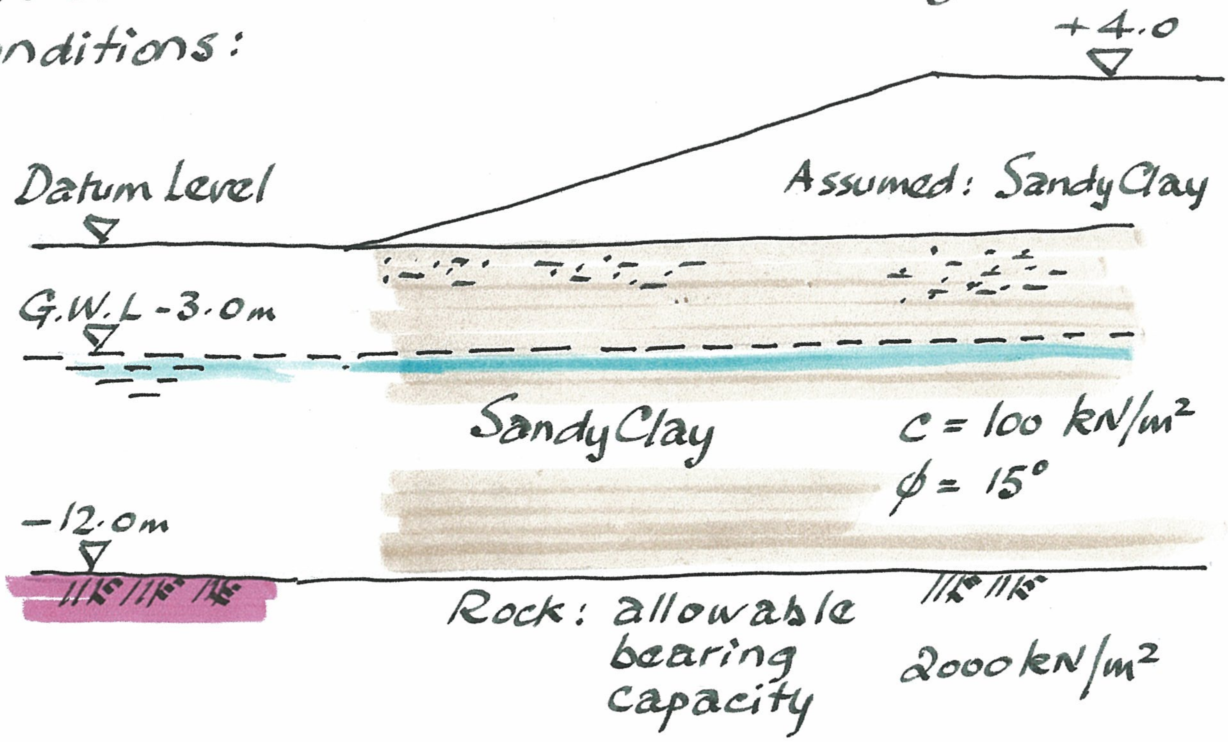
If this option is developed, calculations [Section 2c] will be needed for a typical reinforced concrete panel – slab, beams and column; a typical truss and post: and foundations. These will be translated into drawings [Section 2d] – a GA. plan and section; a typical floor panel [so that a bending schedule 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.



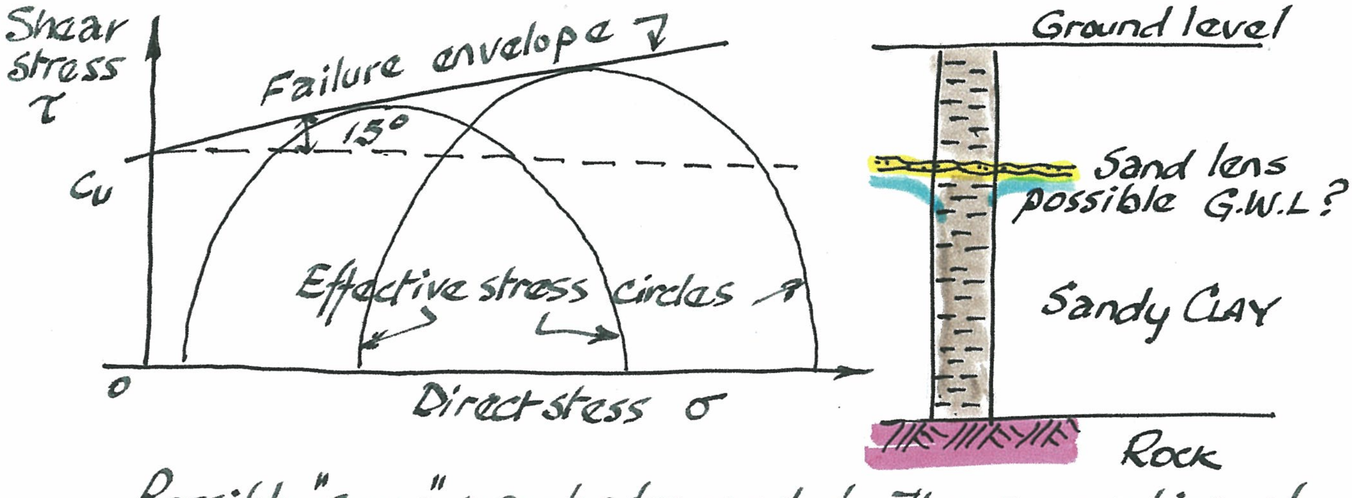
If this option is developed, calculations will be needed [Section 2c] for the reinforced concrete frame and panel - slab, beams and column - and the two external portalised supports: and their foundations! Depending upon which type of roof is chosen, either the triangulated truss and purlins or the rafters 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:



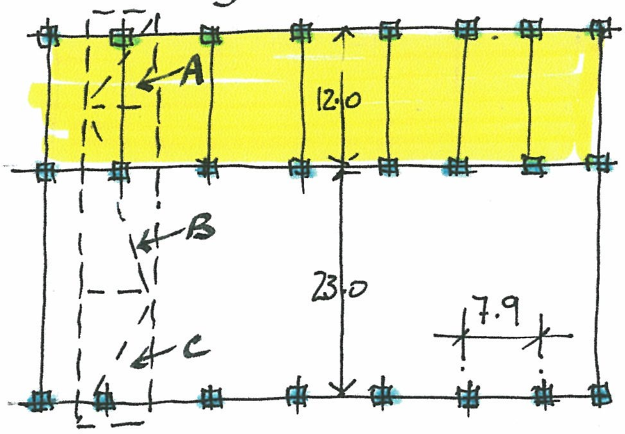
With a cohesion value of $100\ kN/m^2$ the clay will be "Firm" to "Stiff". The angle of shearing resistance, $\phi = 15°$, indicates that the effect of direct stress is minimal; i.e. the sand has little influence on the strength – probably in thin layers or lenses within the clay. This would account for the reported ground-water level which is unusual in a clay soil.

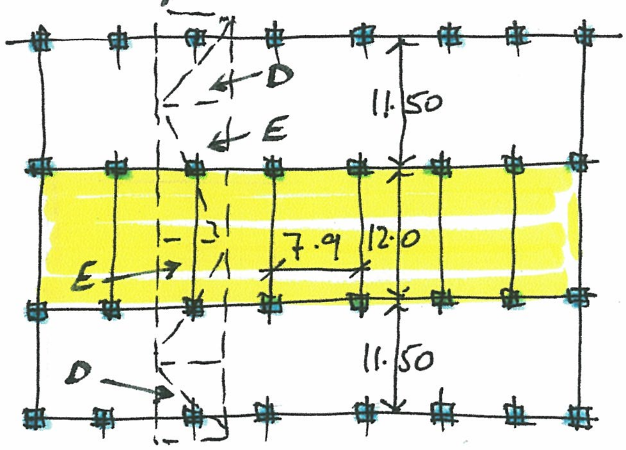


Possibly "some" may be trapped by the suggestion of "sand" and a high G.W.L which would normally halve the bearing capacity, but in this case do not (in my opinion) apply.

Q5/2009 RAW

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:

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

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

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

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

$\underline{\underline{2395}}$

Area B

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

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

$\underline{\underline{6980}}$

Area C

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

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

$\underline{\underline{1046}}$

Area D

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

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

$\underline{\underline{523}}$

Area E

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

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

$\underline{\underline{4688}}$

1 tonne $\doteq$ 10 kN

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

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

$+ (20.0 \times 0.150) = 3.0$

$+ (20.0 \times 0.020) = 0.4$

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

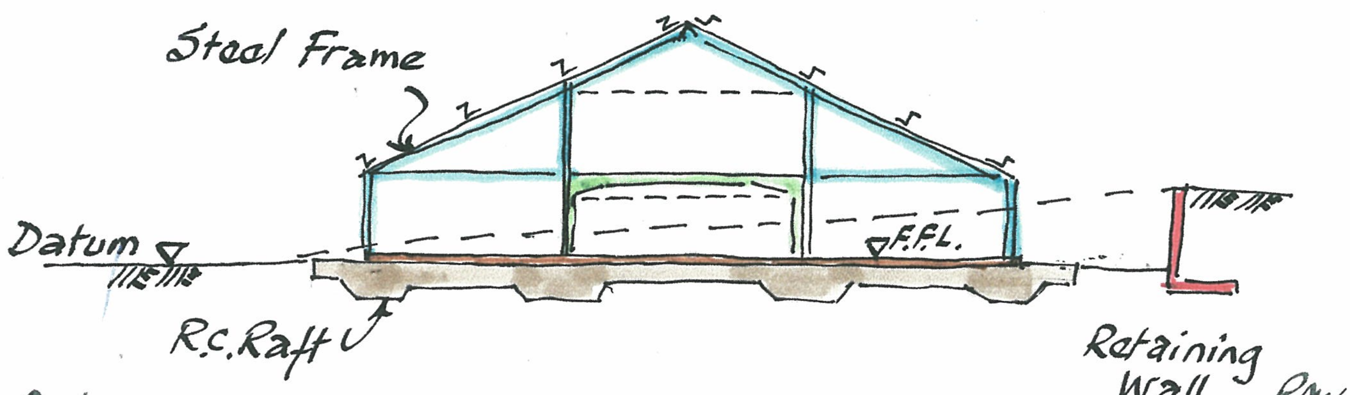
Typical panel/Col $= 25.0 \times 7.9 = \underline{\underline{198 \text{ kN}}}$

Area A	2395 + 2 × 198	= 2791 kN.	This should be about right!
Area B	6980 + 2 × 198	= 7376 kN	
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].



Q5/2009 RAW

Total raft area = 62.0 * 41.0 = 248m²

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

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

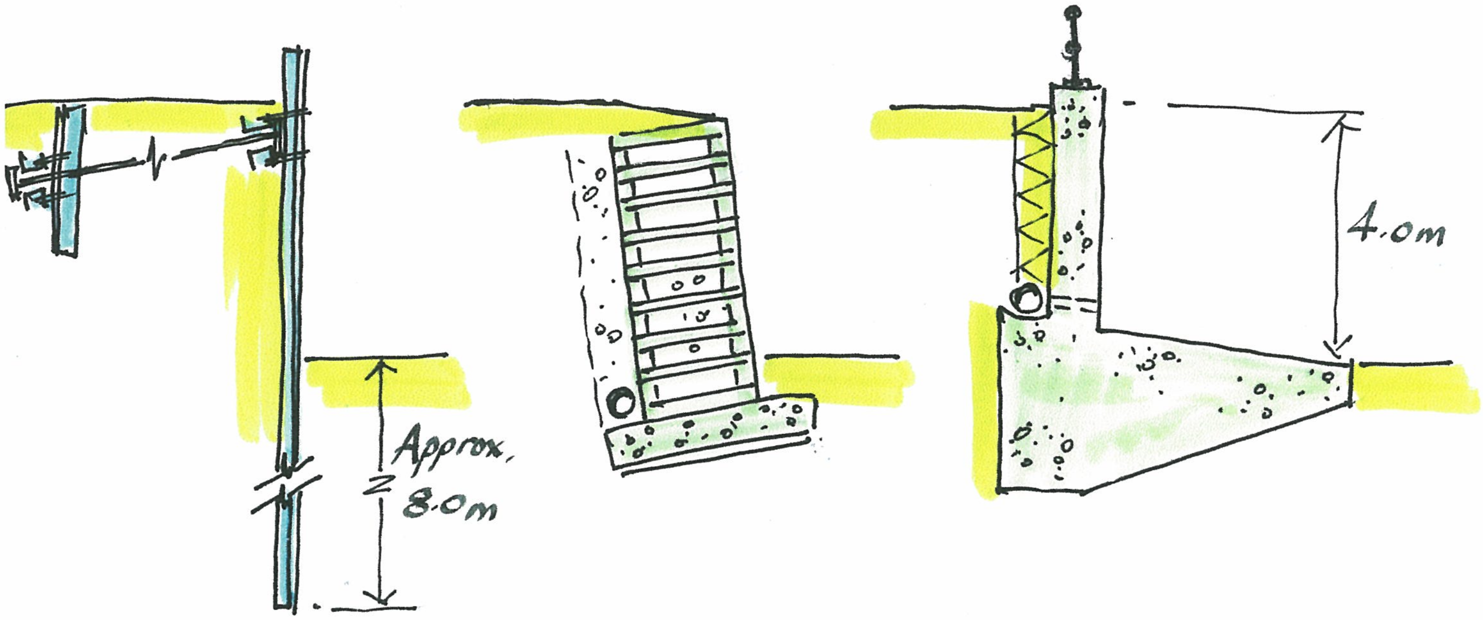
* Spread footing on clay: $q_{allowable} = 2 \times C_u = 2 \times 100\ kN/m^2$

* Fiona Cobb, "Structural Engineers Pocket Book".

$= 200 > 47$

∴ satisfactory.

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

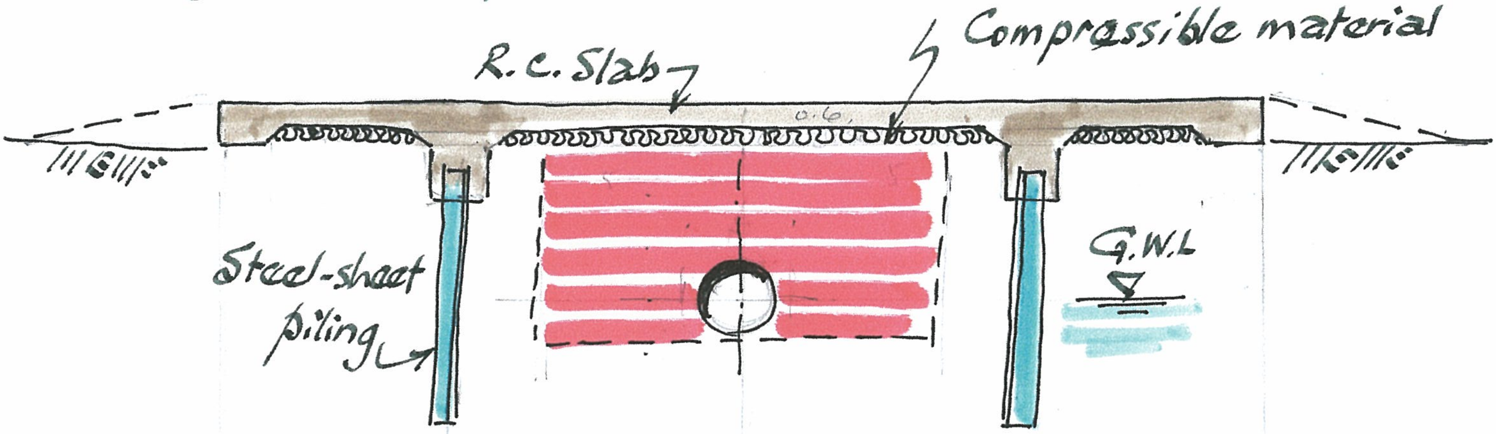


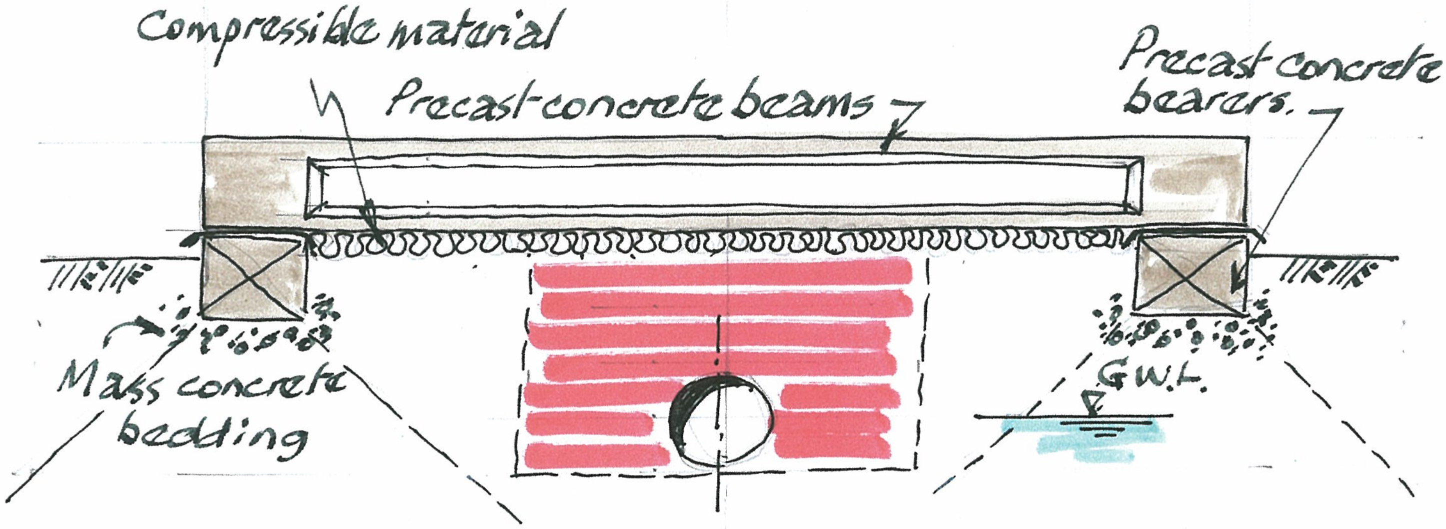
Steelsheet piling   Crib wall   R.C. Cantilever

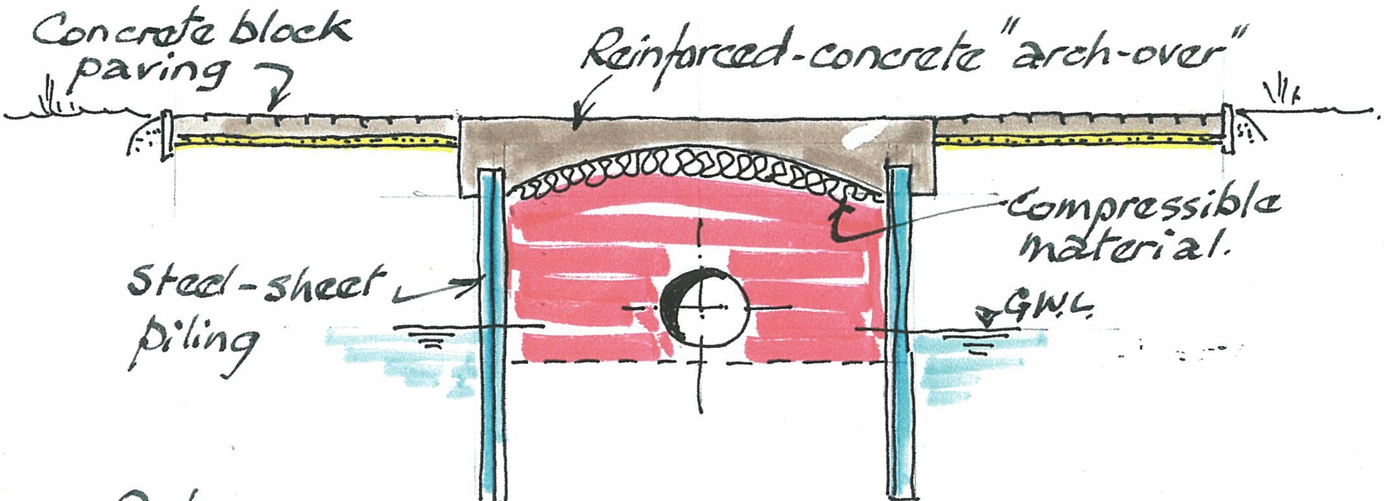
Appropriate calculations would be done in Section 2e. Appropriate sections would be shown in Section 2d. The Method Statement [Section 2e] would explain how the wall would be built. The outline programme would determine a duration and insert this into the sequence of the works – probably: bulk excavation,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







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".