Scenario Week: Report

Group 1 B

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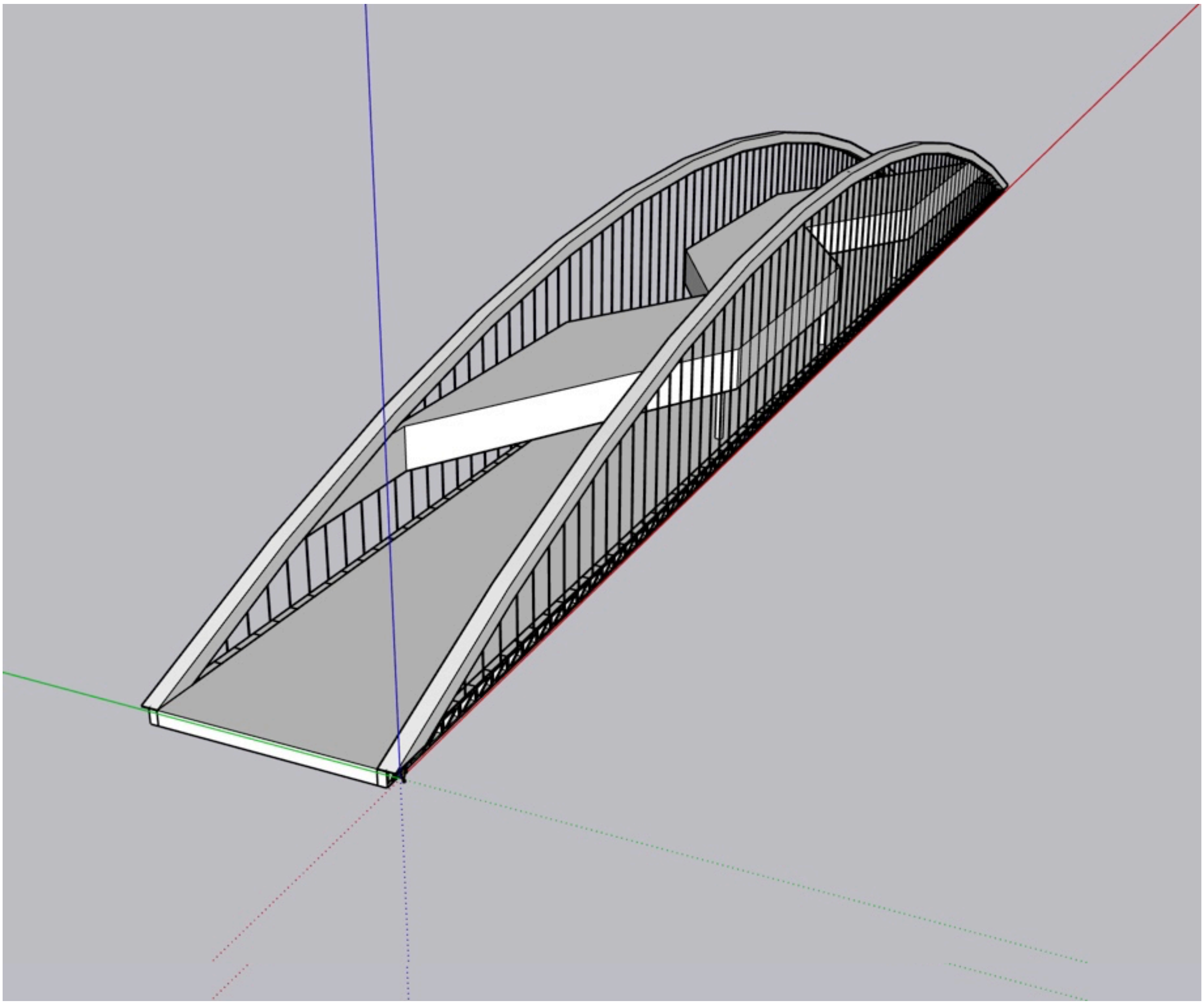
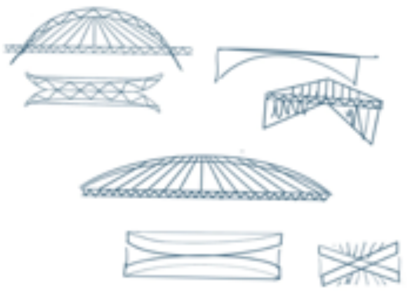
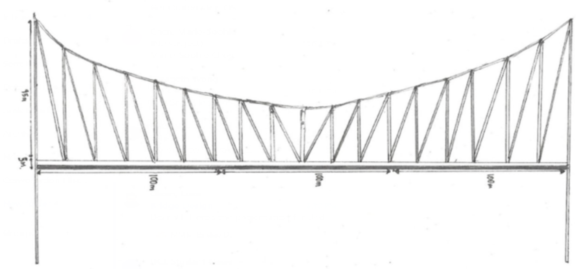


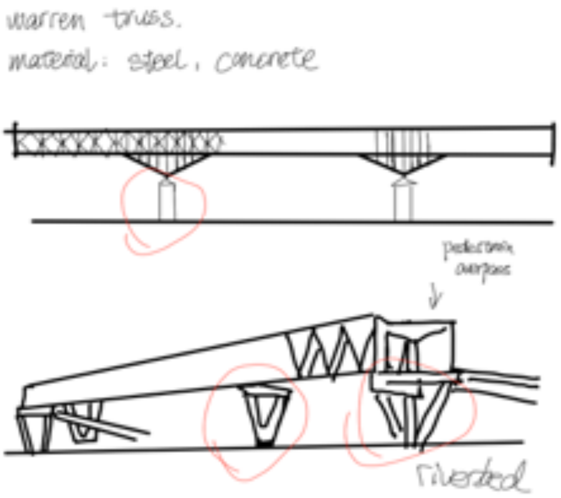
The aim is to design a bridge above the Thames, spanning 300m long.

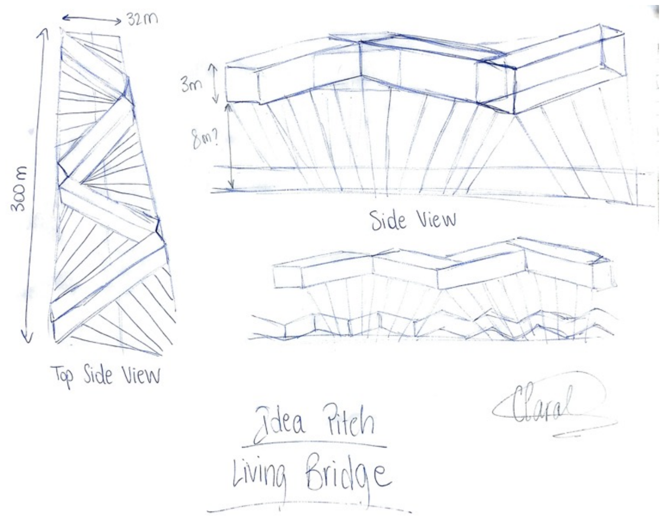
DESIGN CONCEPT

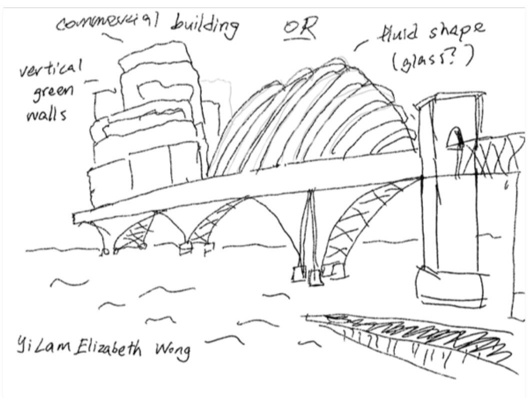
First approach:

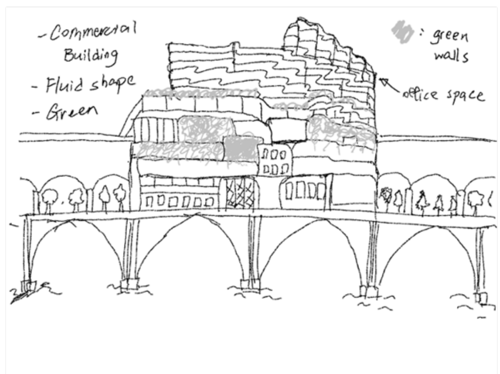






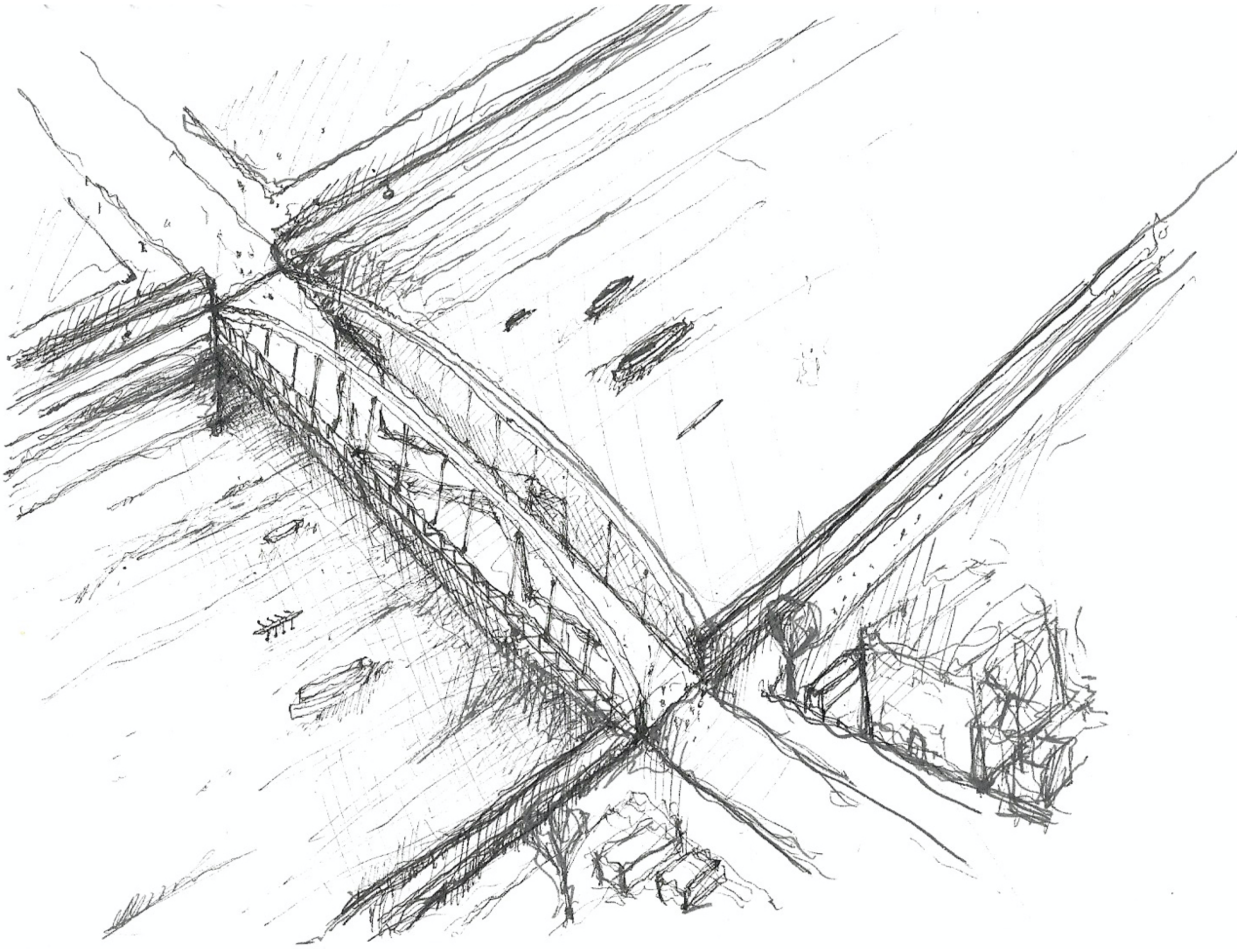




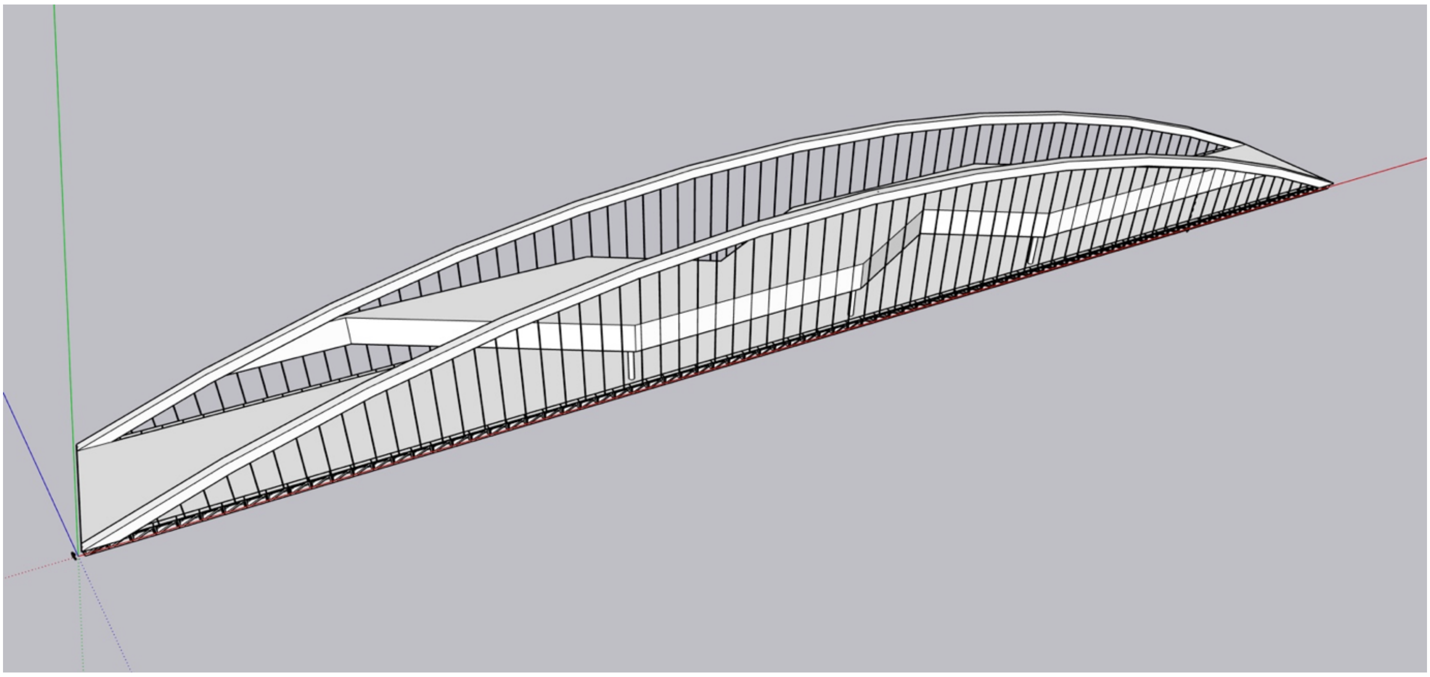


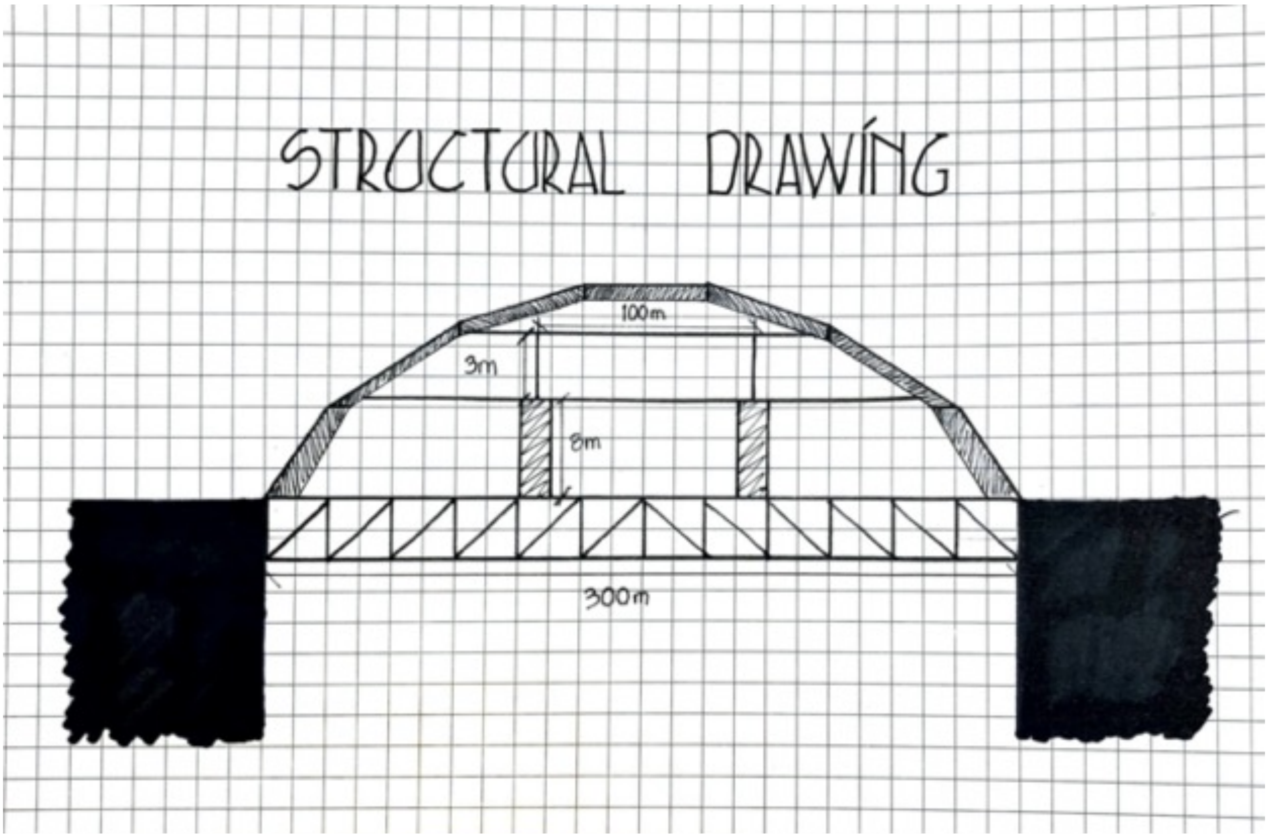
We have chosen an arched cable stayed bridge design which suspends over a trussed deck, and also supports a zigzag elevated exhibition space. The gallery consists of a walkthrough which can be accessed through stairs on either sides. One must enter on one side and walk through the gallery till the exit on the other side.

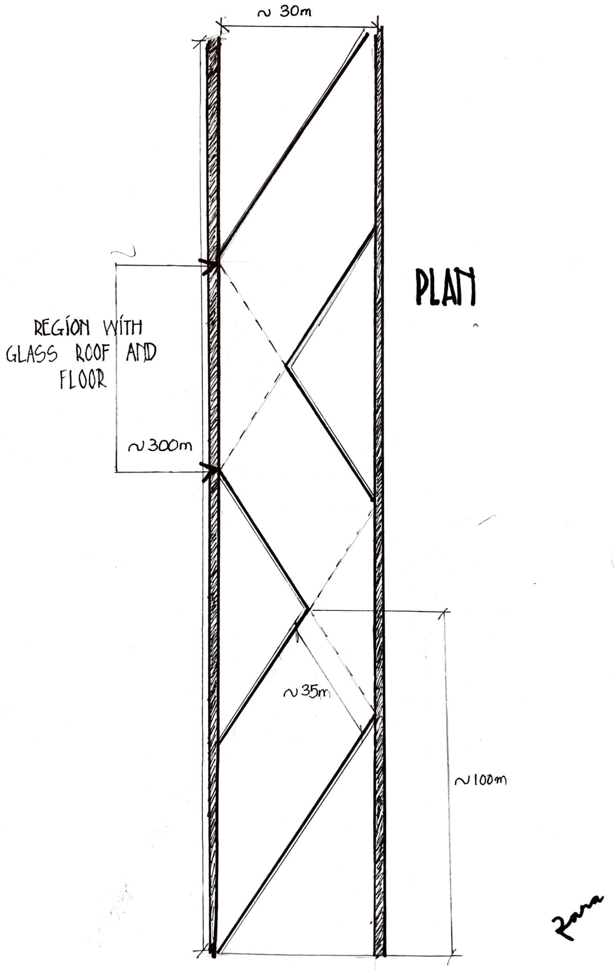
Sketch of the bridge



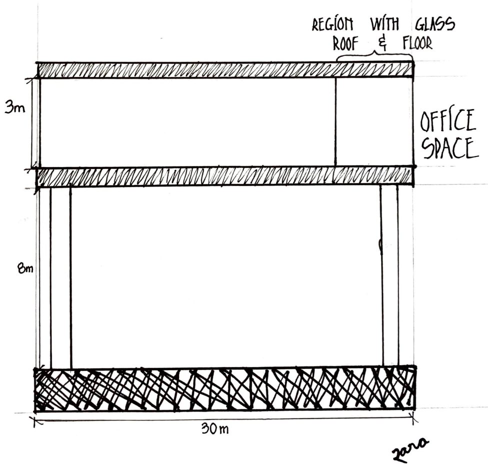
Digital model







ELEVATION SECTION



Material Choice:

- The arch, the trusses and the cables will be made of duplex stainless steel because of its high tensile strength.

Duplex stainless steels[I]:

The grades most commonly used in bridges are 1.4462 and 1.4162. This is based on its corrosion class and the type of environment the bridge is built in: urban or industrialised areas with moderate pollution use duplex grades of 1.4162 and 1.4362 (C4); severely and moderately polluted and industrialised atmospheres also use 1.4462.

Grades suitable for a higher class may be used for lower classes but this is not cost effective. Thus, the stainless-steel duplex grade more apposite for the living bridge is 1.4162. This also takes into account that the location where the bridge is intended to be built has moderate pollution and is in an urban and industrialised area.

Although the unit weight embodied values of duplex stainless steels are higher than carbon steels, duplex stainless steels are lighter and have equivalent load bearing capacities.

Environmental benefit of duplex stainless-steel bridges:

Stainless steel is 100% recyclable without any loss of performance and change in material properties. This benefits the environment by reducing the consumption of non-renewable resources.

Duplex stainless steel has a high strength to weight ratio and therefore less material can be used in order withstand loads. Furthermore, it is able to be built over large spans and therefore simplifies construction. This also cuts down the environmental impact it has on the river.

The lighter construction reduces the required foundation, reducing construction time and also minimising ground disturbance which thereby reduces excavation, transportation and disposal costs.

The reduction in weight will reduce the emissions and energy used both directly in the material and also indirectly due to reduced transportation which emits CO2.

Durability and maintenance:

Because of its composition, the duplex stainless steels are resistant to corrosion cracking. This makes the material more durable in the environment above the river.

Stainless steel bridges are generally easily adaptable to suit changes in road configurations and increased loading, ensuring that they are used for the full intended design life.

The duplex stainless-steel brides are very reliable since they can be repaired whilst staying in service. It also can absorb loads well above design values without having the structure collapse.

Aesthetics:

Stainless steel can for complex geometries and curved alignments, thus are often chosen for landmark bridges. In addition, the fact that there is a range of types of polishing finishes, this material can be used for different aesthetic effects.

- Aluminium alloy is used in the construction of the office because of its intrinsic lightness property as well as its longevity and resistance to corrosion. This material has a high strength to weight ratio, and is also corrosion resistant[II].

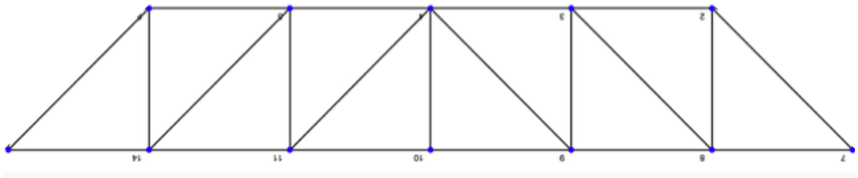
- The bridge deck is covered with a layer of recycled concrete mixed with new concrete. The recycled concrete is mixed with the new, maintaining concrete's essential qualities of strength and resistance. It is often used as a bottom layer road base[III].

Element	Material	Youngs Modulus, E (GPA)	Yield Stress	Density (g/cm^3)	Tensile Strength (MPa)	Reasoning
Arch	Duplex Stainless-Steel Grade: 1.4462	200	450 Min MPa	7.8	650 Min MPa	High strength to weight ratio
Cables	Duplex Stainless Steel: 1.4462	200	450 Min MPa	7.8	650 Min MPa	High Tensile Strength and therefore able to withstand the forces applied from the deck.
Trusses	Duplex stainless. Grade: 1.4462	200	450 Min MPa	7.8	650 Min MPa	High Density and tensile strength. Thus, less material can be used to withstand the same force metals with more material can.
Buildings	Aluminium alloy	75	265	2.7	1360	Low Density relative to other metals and therefore reduces the load on the bridge/ lighter weight
Deck/ Slab	Concrete	31.5	46	2.4	10.5	High compressive strength and therefore able to withstand the load of the live load

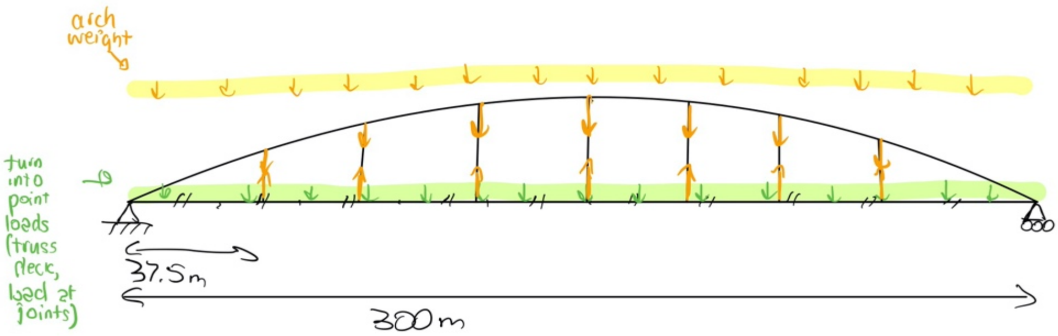
Table 1: Properties of materials used[I IV]

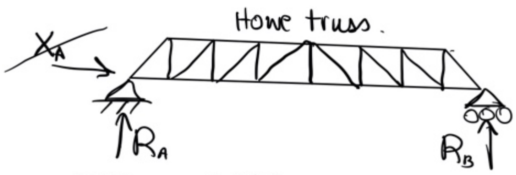
STRUCTURAL CALCULATIONS

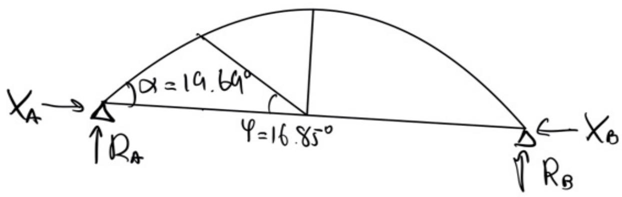
The type of truss used is the Howe Truss.



The configuration of the truss is very efficient, reducing its self-weight and making the structure easy to construct, due to its vertical members being in tension while the diagonal members are in compression.
For a more stable structure, Cables are used. Being in tension, they provide support to the deck of the bridge. They are usually used on long span bridges.



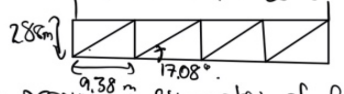




$\Sigma F_x = 0 \Leftrightarrow X_A = 0$

so $R_A = R_B$.

we simple the model for calculations.
we divide the bridge into 8 sections with 7 cables and there are 4 trusses at each section



since the bridge is symmetrical, we also assume a symmetry of forces for the 2 sides.

1) Live load and Dead load calculations/approximations

In order to find the mass of the dead load of the bridge, the values for the densities for each material used in the bridge were obtained from tabulated values from sources. This included the concrete for the slab of the bridge, double duplex stainless steel, which was used for the cables, the arch, the trusses (the deck of the bridge) and aluminium for the outer frame of the buildings (other materials for the buildings were neglected due to the predominant mass of the buildings deriving from the aluminium frame). In order to calculate the mass of each object, we used the equation 'density=mass/volume'. Thus, via manipulation we were able to obtain the mass of the dead load of the bridge. These values were then multiplied by the gravity value of 9.8 N/kg.

To find the weight of the arch, we used the software 'GeoGebra' in order to obtain the arc length. We then applied the thickness of the beam to the arc length which is of '0.75m'. The diameter of the beam was assumed by looking at similar tied-arch bridges and referencing the diameter of the Lowry Avenue bridge. The mass was then obtained from manipulation of the equation 'density=mass/volume.

The live load (pedestrians/ occupants of the bridge) was approximated by using the value of '5kN/m^2'. This is the value obtained from when the bridge is experiencing a high amount/traffic of people.

The calculations obtained allowed us to obtain the uniform distributed load on the bridge by dividing the total load by the number of joints of one side of the truss. Thus, one was able to obtain the values of the reaction forces at the supports. Additionally, the uniform distributed load of the arch was also accounted for in the resultant forces of the supports. The supports of the bridge were pinned, and roller supports. The roller supports were used as a result of the bridge expanding and contracting under different environments/temperatures. Hence, the bridge cannot be fixed or else it will fracture the supports at the banks of the bridge as a result of expansion arch: arch length = l_{arch} = 307,94 m

diameter of beam d = 0,75 m   r = 0,375 m

$m_{arch} = l_{arch} \times r^2 \pi \times \rho = 307,94 \times 0,375^2 \pi \times 7805 =$

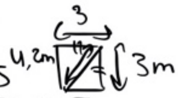
1061,82 tons × 2.

concrete slab: l_{slab} = 300 m   width w = 30 m   thickness t = 0,03 m

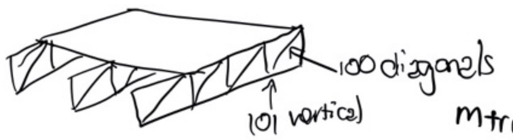
$m_{slab} = l_{slab} \times w \times t \times \rho_{concrete} = 300 \times 30 \times 0,03 \times 2400\ kg/m^3$

= 648 000 kg = 648 tons.

trusses for deck: 100 elements for truss



thickness of stick d = 0,25 m   r = 0,125 m



$V = r^2 \pi\ (300m \times 2 + 3m \times 101 + 4,2m \times 100)$

$V = 194,828\ m^3$

$m_{trusses} = \rho_{steel} \times V \times 3 = 7805 \times 194,828 \times 3$

$m_{trusses} = 1,52063 \times 10^6$ kg

$m_{trusses}$ = 1520,63 tons

building: $\rho_{aluminium} = 2700\ kg/m^3$

Surface area A = 10810 m^2 (Geogebra)

t = 20 cm = 0,02 m

$V = A \times t = 10810 \times 0,02 = 216,2\ m^2$.

$m_{building} = \rho_{aluminium} \times V$ = 583740 kg = 583,740 tons.

m_{bridge} = 3814,19 tons

$W_{bridge} = 3814190 \times g$ = 37 379 062 N.

Live load ⊕ dead load calculation.

$m_{truss} + m_{concrete} + m_{building}$ = 583.740 + 1520.63 + 648

= 2752.37 tons.

= 2752 370 kg.

$W_{truss,concrete,building}$ = 2752 370 × 9,8 N/kg

= 26 973 226 N = 26973 kN.

pedestrian load 5 kN/m^2.   A = 30 × 300 = 9000 m^2.

W_p = 5 × 9000 = 45000 kN

W_{tot} = 45 000 + 26 973 = 71973 kN.

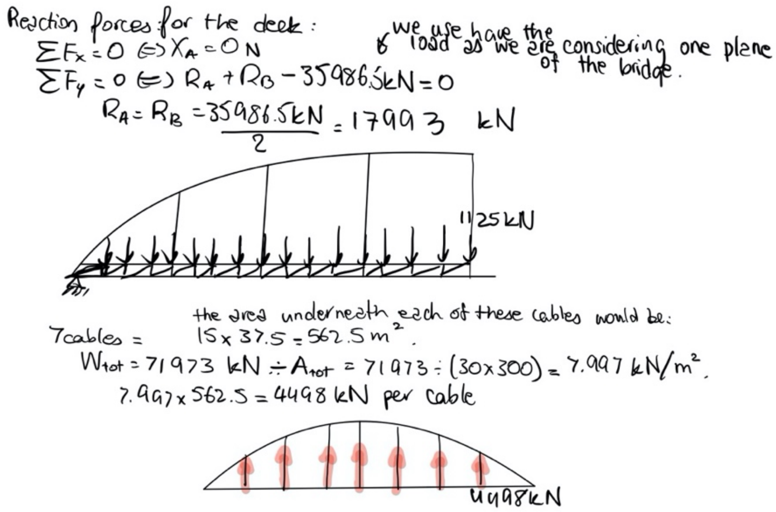
8 × 4 = 32 joints on one plane of truss.

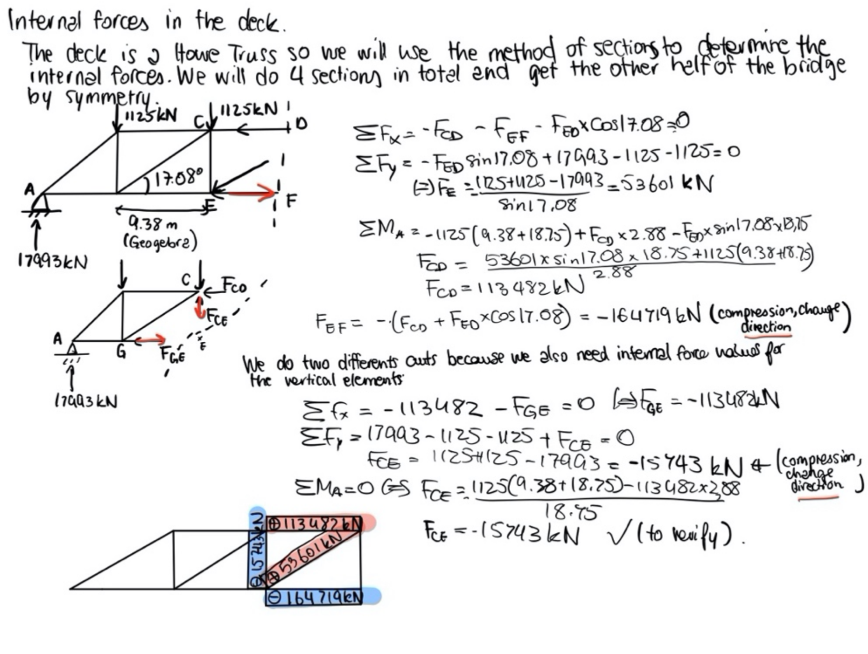
32 × 2 = 64 joints

W_{tot} ÷ 64 = 71973 ÷ 64 = 1124,58 kN. for each joint

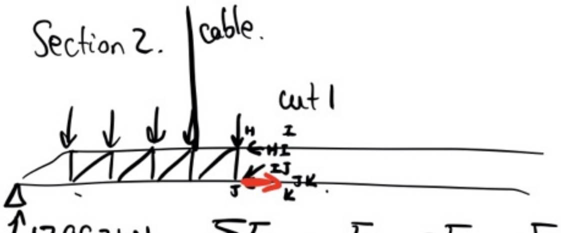
2) Calculations for the internal forces in the trusses

The internal forces of the truss elements were calculated via changing the distributed load on the bridge into point loads; the point loads are applied to each joint. Thus, one was able to calculate the internal forces from the resultant forces of the supports and the point loads at each support. The deck consisted 32 trusses: in order to calculate/ analyse the internal forces in the elements, the method of sections was used at four sections across the beam. This enabled us to analyse the variation of the internal forces across the truss. We only considered one side of the bridge due to how the internal forces of the truss system has an axis of symmetry in which the internal forces and whether the element is in tension or compression is the same. 'GeoGebra' was also used in order to obtain values for the angles of the diagonal truss elements due to their rectangular shape (2.88m in height and 9.38m in length). The first two sections were hand calculations while sections 3 and 4 uses Matlab to facilitate calculations.





Section 2.



$$\Sigma F_x = -F_{HI} - F_{JK} - F_{IJ} \times \cos 17.08 = 0$$

$$\Sigma F_y = -5 \times 1125 + 17993 - F_{IJ} \times \sin 17.08 = 0$$

$$F_{IJ} = \frac{5 \times 1125 - 17993}{\sin 17.08} = 42110 \text{ kN}.$$

$$\Sigma M_A = F_{HI} \times 2.88 - 1125(15 \times 9.38) - F_{IJ} \times \sin 17.08 \times 9.38 \times 5 = 0$$

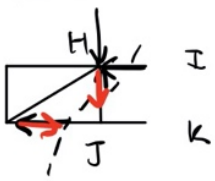
$$F_{HI} = \frac{1125(15 \times 9.38) + 42110 \times \sin 17.08 \times 9.38 \times 5}{2.88} = 256370 \text{ kN}$$

$$F_{JK} = -(F_{HI} + F_{IJ} \times \cos 17.08) = -296\,623 \text{ kN (compression)}$$

$$\Sigma M_J = F_{HI} \times 2.88 - 17993 \times 9.38 \times 5 + 1125(10 \times 9.38) = 0.$$

$$F_{HI} = 256370 \text{ kN}$$

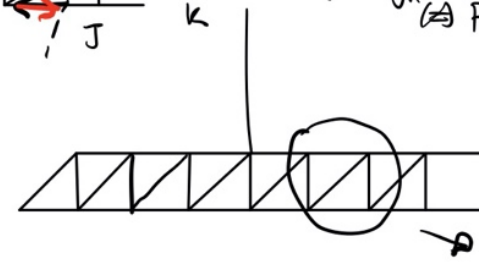
cut 2.

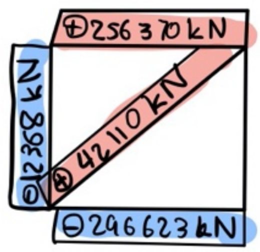


$$\Sigma F_x = -F_{HI} - F_{IJ} = 0.$$

$$\Sigma F_y = F_{JH} + 17993 - 5 \times 1125 = 0$$

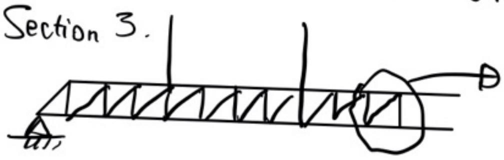
$$\Leftrightarrow F_{JH} = 5 \times 1125 - 17993 = -12368 \text{ kN (compression)}$$

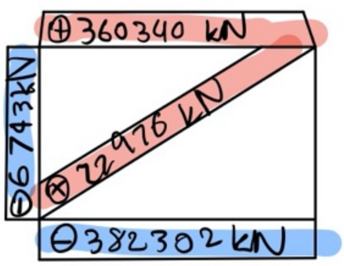




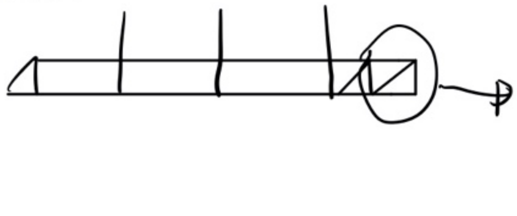
We use the same method for the other two sections, where we used Matlab to calculate:

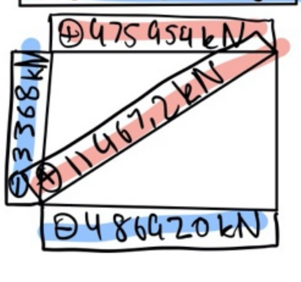
Section 3.





Section 4





3) Calculations for the tension in the cables

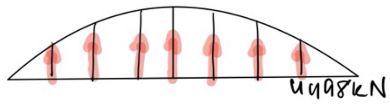
The cables play a significant role in carrying the weight of the dead and live load of the bridge: the cables are attached to the deck of the bridge and transfer the load of the deck containing the dead/live load to the arches. The arches then transfer this force to the supports of the bridge. In order to calculate the force in which the cable carries, on must consider the area of the bridge that each cable supports. This was obtained by first calculating the area of the bridge. We then assumed and calculated how many cables support the weight of the bridge. The area is then divided by the number of cables in which tells us how much area is supported by a single cable. We then were able to obtain the load that each cable carries (all of them carrying equal loads) by converting the distributed loads into point loads by multiplying the length of the supporting area by the distributed force on the deck. Hence, the tensile forces can be calculated via an equilibrium equation in which the internal forces within the element must equal the external forces applied (in the cable).

the area underneath each of these cables would be:

7cables = $15 \times 37.5 = 562.5\,m^2$.

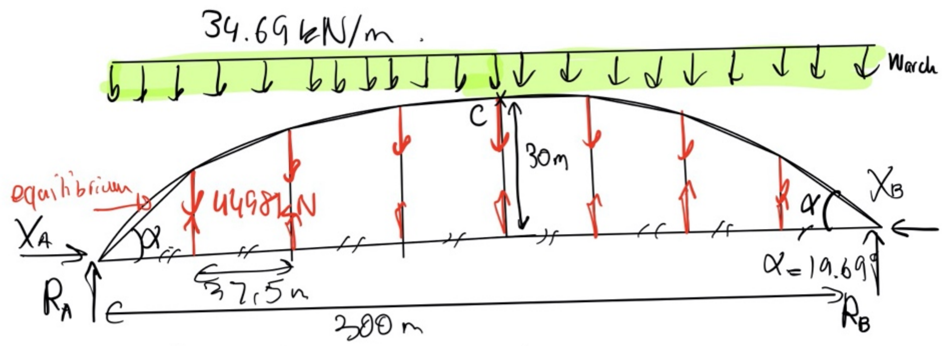
$W_{tot} = 71973\ kN \div A_{tot} = 71973 \div (30 \times 300) = 7.997\ kN/m^2$.

$7.997 \times 562.5 = 4498\ kN$ per cable



4) Calculation for the internal forces within the arch

The arch has a distributed load from its self-weight which is applied to the supports of the deck. The internal forces at any section of the arch will have an actual shear force, axial force bending moment. Uniform load is also applied to the cables in order to ensure the cables are in equilibrium. The forces along the bridge are distributed uniformly so for the reaction forces, a compressive force from both ends of the arch and a reaction force. The compressive force is compensating each other Uniform load is calculated over the arch by the weight of the arch divided by the length of the bridge. Reaction forces are calculated via equilibrium equations (knowing that it’s equal to zero). The equilibrium equations can be found by calculating the moments along the arch. The moments in the arch equal to zero in the centre of the arch. Once u calculate the reaction forces you can calculate the internal forces and take into account symmetry; two sections are made of half of the arch to calculate the internal forces. Then a summation is made for the actual forces. GeoGebra was used to determine the angles of the arch.



Calculation of the uniform load on the arch:

$m_{arch} = 1062$ tons $= 1062000$ kg.

$W_{arch} = 1062000 \times 9.8$ N/kg $= 10407600$ N $= 10407,6$ kN.

$w_{arch} = W_{arch} \div$ length of bridge $= 10407,6 \div 300 = \boxed{34,69 \text{ kN/m}}$

Reaction forces at the end of the arch:

$R_A = R_B \qquad X_A = -X_B$

$\Sigma F_y = R_A + R_B - 34.69 \times 300 - 4498 \times 7 = 0$

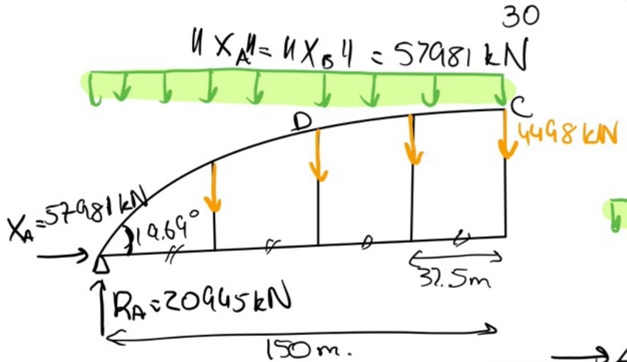
$R_A + R_B = 41893 \text{kN} \Leftrightarrow R_A = R_B = \frac{41893}{2} \text{kN} = 20945 \text{kN}$

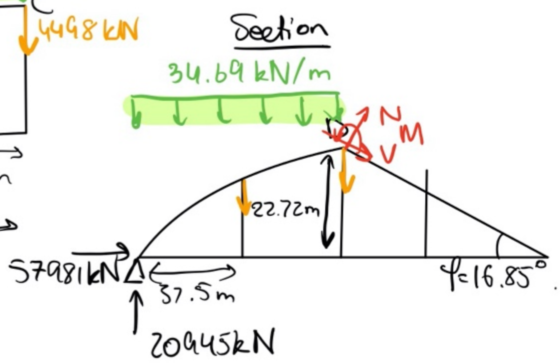
we can get X_A from $\Sigma M_c = 0$

$\Sigma M_c = -R_A \times 150 + X_A \times 30 + 4498 \times 37.5 \times 6 + 34.69 \times 150m \times 75m = 0$

$X_A = \frac{R_A \times 150 - 4498 \times 37.5 \times 6 - 34.69 \times 150 \times 75}{30} = 54981 \text{kN}.$

$\| X_A \| = \| X_B \| = 57981$ kN





Internal forces of point D.

$\Sigma M_D = -R_A \times 37.5 \times 2 + X_A \times 22.72 + 4498 \times 37.5 + 34.69 \times 75 \times 37.5$

$\Sigma M_D = 12693.9$ kN/m

$\Sigma V_D = R_A \sin\varphi - X_A \cos\varphi - 2 \times 4498 \times \sin\varphi - 34,69 \times 75 \times \sin\varphi =$

$\Sigma V_D = -52800$ kN.

$\Sigma N_D = -R_A \cos\varphi - X_A \sin\varphi + 2 \times 4498 \times \cos\varphi + 34.69 \times 75 \times \cos\varphi$

$\Sigma N_D = -25758$ kN.

5) Allowable stress in the material

The bridge is mainly made of three materials: stainless steel, concrete and aluminium alloyds. We can calculate the allowable stress in the material with the following formula:

$\sigma_{all} = \frac{\sigma_y}{factor\ of\ safety}$, and results are to 1 decimal place

1. For stainless steel arch and truss beams:
   The maximum yield stress $\sigma_y = 585$ MPa[V], factor of safety is usually taken as 6, therefore:

$$\sigma_{all} = \frac{\sigma_y}{factor\ of\ safety} = \frac{585}{6} = 97.5MPa$$

2. For concrete deck:
   The maximum yield stress $\sigma_y = 46$ MPa[VI], factor of safety is usually taken as 1.1, therefore:

$$\sigma_{all} = \frac{\sigma_y}{factor\ of\ safety} = \frac{46}{1.1} = 41.8MPa$$

3. For aluminum alloys:
   The maximum yield stress $\sigma_y = 325$ MPa[VII], factor of safety is usually taken as 1.5, therefore:

$$\sigma_{all} = \frac{\sigma_y}{factor\ of\ safety} = \frac{325}{1.5} = 216.7MPa$$

6) <u>Buckling/ critical load of the elements</u>

The buckling load was calculated for the predominant members which were affected by compressive forces. These members were the vertical members in the truss in which experienced a point load thereby compressing them. These members are pin connected and thus one can obtain the fixative conditions for pinned connections at both ends which is '1.0'. The k values determine the horizontal displacement of the column which is dependent of the type of support. In order to calculate the critical load 'P_{cr}', one must use the formula$\frac{\pi^2 \cdot E \cdot I}{(k \cdot L)}$. Thus, one is able to identify the maximum load/limit that a column can withstand until buckling occurs.

In order to assess the buckling in the truss members of the howe truss, we considered only the members which are in compression. Furthermore, we used the method of sections to analyse the change in internal compressive forces across the truss. Thus, we obtained values for the vertical member and horizontal member under compression at each section. The moment of inertia was calculated via using the formula $\left(\frac{\pi \cdot 0.25^4}{64}\right)$ which is the moment of inertia for the solid rod.

The critical load is calculated as $\frac{\pi^2 \cdot (200 \cdot 10^6) \cdot \left(\frac{\pi \cdot 0.25^4}{64}\right)}{(1 \cdot 2.8)^2} = 48277.37 = \frac{48277.37}{0.05} = 965547.4kPa$

Section	Truss component	Compressive Stress (kPa)	Exceeded/Not exceeded (critical load)
1	Diagonal	2269640	Exceeded
	Horizontal	1072020	Exceeded

Section	Truss component	Stress (kPa)	Exceeded/Not exceeded
2	Diagonal	842200	Not exceeded
	Horizontal	5127400	Exceeded

Section	Truss component	Stress (kPa)	Exceeded/Not exceeded
3	diagonal	459400	Not exceeded
	Horizontal	7206800	Exceeded

Section	Truss component	Stress (kPa)	Exceeded/Not exceeded
4	diagonal	229344	Not exceeded
	Horizontal	9519080	Exceeded

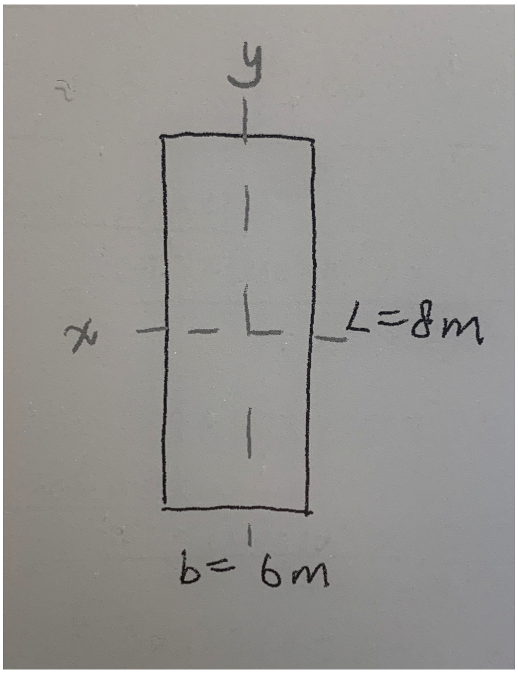
One can then evaluate that the horizontal components are subject to a higher internal compressive force/stress as the distance increases to the centre of the truss from the supports. Conversely, there is a decrease in the compressive internal force/stress in the diagonal components, thus displaying a negative correlation between the horizontal and diagonal members as the distance from the support's increases. In order to reduce the stress in the members of the trusses, one must increase the number of trusses within the bridge in which decreases the load applied to the joints in the bridge (more joints, more distribution of the load). This therefore prevents buckling (displacement in the y axis of the element) and the members exceeding the critical load.

Buckling Strength of the Columns supporting the building

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2}, \text{ where}$$

- E = modulus of elasticity of steel = $210GPa$
- L = Length of the column = $8m$
- K = End Fixity Condition = 0.5 for fixed ends column
- I = moment of inertia

The following diagram shows the dimensions of a column



The moment of inertia along the x-axis and y-axis can be found with the following equations below respectively:

$$I_x = \frac{bh^3}{12} \text{ and } I_y = \frac{b^3h}{12}$$

With b = width = 6 m and h = length = 8 m,

$$I_x = 256$$
$$I_y = 144$$

Buckling about y-axis

$$P_{cr,y} = 1.865355232 * 10^{10}$$

Buckling about x-axis

$$P_{cr,x} = 3.316187079 * 10^{10}$$

The smaller load value of the two would give the critical load P_{cr} , which is

$$P_{cr} = 1.86 * 10^{10} \text{ (2s.f.)}$$

The critical stress value can then be calculated

$$\sigma_{crit} = \frac{P_{crit}}{A}$$
$$\sigma_{crit} = \frac{1.86 * 10^{10}}{8 * 6}$$
$$\sigma_{crit} = 3.886156733 * 10^8 kPa$$
$$\sigma_{crit} = 3.89 * 10^8 kPa$$

GEOTECHNICAL CALCULATIONS

Foundation Choice:

When considering the foundation for the bridge, we must first investigate the soil at the chosen location. The soil is usually clay, sand or a mixture of sediments from the disintegration of rocks.

There are mainly two types of foundations: ‘spread’ and ‘piled’ foundation.

Spread footings are consider as a shallow foundation, and are used when the bedrock is close to the surface. They consist in large blocks (often concrete) which spread the weight of the structural element into a larger area of the soil, thus preventing it from sinking.

Piled foundations are long slender columns that convey the loads to lower depths. This type of foundation transfers the loads to the soil through bearing pressure and friction, resulting in a substantially more stable foundation.

We will first examine the settlement due to a shallow foundation; if the settlement appears to be too high, piled foundations will be used since the settlement is null.

(“Deep Foundations and Bridge Construction - Madrid Engineering Group”)

Before settlement calculations:

To calculate the overall weight of the bridge and the foundation, we need to subtract the weight of the soil excavated from the basement from the overall weight of the building with the following equation:

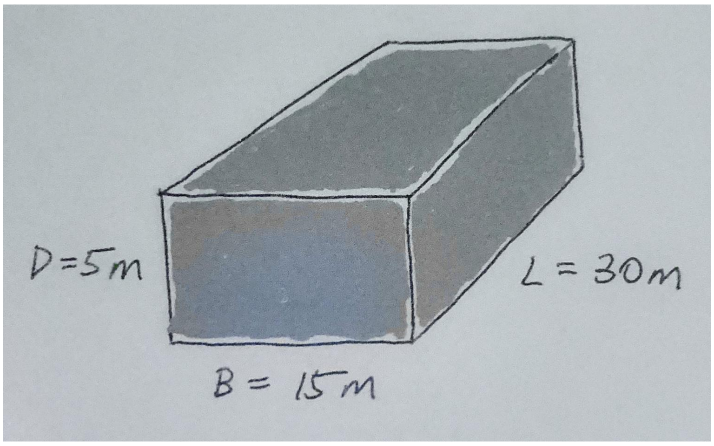
$$W_{net} = W_b + W_f - W_s, \text{ where}$$

Wb: Weight of the bridge
Wf: Weight of the foundation
Ws: Weight of the soil

The mass of the bridge m_b from structural calculations is 3814.19 tonnes (3814.19 *10^3 kg).

Weight of the bridge W_b = 37417.2039 kN

The foundation we chose has a shape of a rectangular cell with the following dimensions:



The foundation will be made according to the assumption that around 20% of the volume of the soil excavated and filled by concrete.

In order to calculate the weight of the soil W_s, the volume of soil excavated V_s and the unit weight of the soil Ys have to be found according to the following equation:

$$W_s = V_s * Ys$$

The Volume of soil excavated V_s =5*15*30 = *2250 m^3*
The Bulk unit weight of the soil = *20 kN/m^3*

The weight of the soil W_s = 45000 kN

The Volume of Concrete (for the foundation) = 450 m^3
Bulk Unit Weight of Concrete = 23 kN/m^3

Weight of the foundation W_f = 10350 kN

Therefore, the **Net Weight W_{net} = 2767.2039 kN**

Settlement Assuming One-Dimensional Loading:

The settlement of foundation will be uniform because the loading is one-dimensional. With the Immediate settlement p_i being 0, we just have to calculate the consolidation settlement p_c for one-dimensional loading.

To calculate the consolidation settlement p_c, the following equation has to be used:

$$p_c = H_i * (e_0 - ef)/(1 + e0), \text{ where}$$

- H_i = Distance from the bottom of the foundation to the dense gravel (end of London clay); H_i = 30 m
- e_0 = initial void ratio at the initial effective vertical stress σ_{v0}'
- e_f = final void ratio at the final effective vertical stress σ_{vf}'

The Weight of the Bridge and Foundation --- **W = 2767.2039 kN** (from previous calculations);

The Area of the Foundation --- *A = 450 m²* ($A = 450\ m^2$)

In order to calculate the final effective vertical stress σ_{vf}' for the settlement calculations, the total stress applied by the bridge and foundation $\Delta\sigma$ has to be known:

Total Stress applied by bridge and foundation (both sides) **$\Delta\sigma$ = 6.149342 kPa**

The Initial vertical stress σ_{v0}' can be found by using the following equation:

σ_{v0}' = Total Vertical Stress at the middle of the clay - Pore Pressure U

*Total Vertical stress at the middle of the clay = unit weight of soil * depth to middle of the clay*

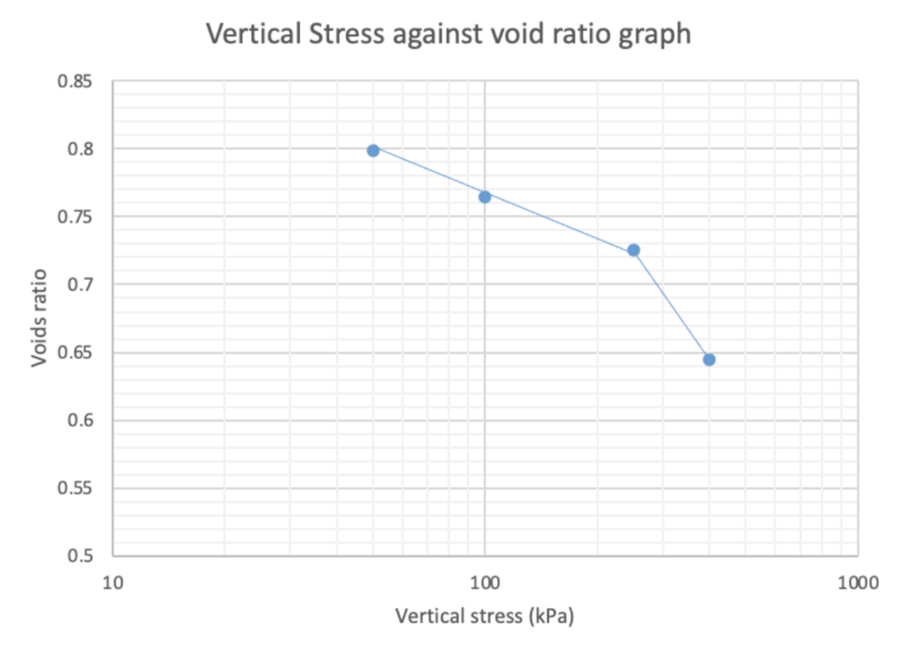
*= 19 m * 20 kN/m³ = 380 kPa* ($= 19\ m * 20\ kN/m^3 = 380\ kPa$)

*Pore pressure U = 9.81 *19 = 186.39 kPa*

Therefore, Initial effective vertical stress (before taking bridge into account) -- **σ_{v0}' = 193.61 kPa**

With the void ratio against vertical stress graph, we can locate our value of initial vertical stress σ_{v0}' and find the initial void ratio e_0 at that point, which is

$e_0 = 0.73995$



The final effective vertical stress σ_{vf}' can be calculated by:

$\sigma_{vf}' = (\Delta\sigma /2) + \sigma_{v0}' =$ 196.684671 kPa

Again, according to the graph: the final void ratio is

$e_f = 0.726$

Therefore, the consolidation settlement p_c is

$$p_c = H_i * (e_0 - ef)/(1 + e0)$$

$$p_c = 0.240524153 \text{ m}$$

$p_c = 0.24$ m (2 s.f.)

Immediate Settlements for Non One-Dimensional Loading

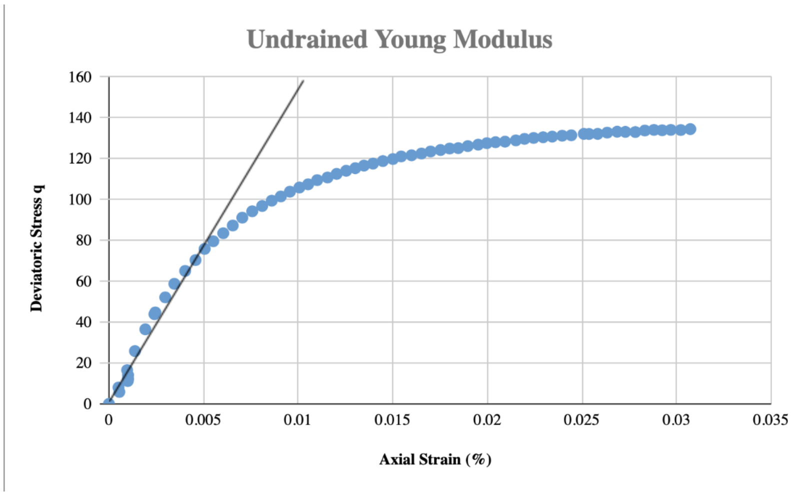
In this case, the immediate settlement pi will not be zero, because there is lateral movement of soil in the ground even for undrained loading (this would be zero in the oedometer/under one-dimensional loading due to rigid wall).

To calculate the immediate settlement p_i for infinite soil depth, the following equation can be used:

$$p_i = [(\Delta\sigma * B) / E_u] * (1 - v_u^2) * I_p \text{ , where}$$

- Poisson's ratio $v_u = 0.5$ (always for undrained loading)
- E_u = Undrained Young Modulus
- B = Breadth (Width) of the foundation = *15 m*
- I_p = Centre Flexible Influence factor (depends on geometry)
- $\Delta\sigma$ = Total stress applied by bridge and foundation (both sides) = *6.149342 kPa*

The undrained Young Modulus E_u can be found by calculating the gradient of the Deviatoric Stress-Axial Strain graph that we created through data provided.



$$\mathbf{E_u = 20664\ kPa}$$

The centre flexible influence factor for the foundation I_p is found according to this table provided:

I_ρ rigid	shape of area	I_ρ flexible			
		centre	mid-edge	corner	average
0.79	circle	1	0.64		0.85
0.82	square	1.12	0.76	0.56	0.95
1.12	rectangle L/B=2	1.53	1.12	0.76	1.3
1.6	rectangle L/B=5	2.1	1.68	1.05	1.82
2	rectangle L/B=10	2.56	2.1	1.28	2.24

Because the foundation has a length of 30m and breadth of of 15m,

$$I_p = 1.53$$

As a result, the immediate settlement p_i would be:

$$\mathbf{p_i = 0.0332\ m}$$

<u>Correction factors for immediate settlements for loads applied below the surface</u>

Using the diagram provided, we use the dimensions of the foundation to find the correction factor. We then multiply the settlement P_i by the correction factor to get the final settlement.

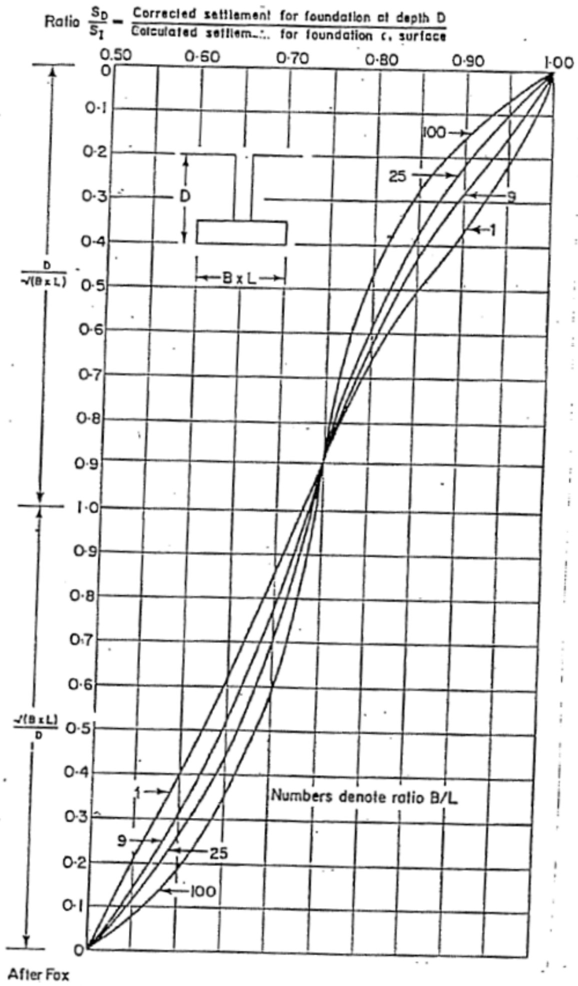
B -- Breadth of foundation = 30m
L -- Length of foundation = 15m
D -- Depth from the surface to the foundation = 5m

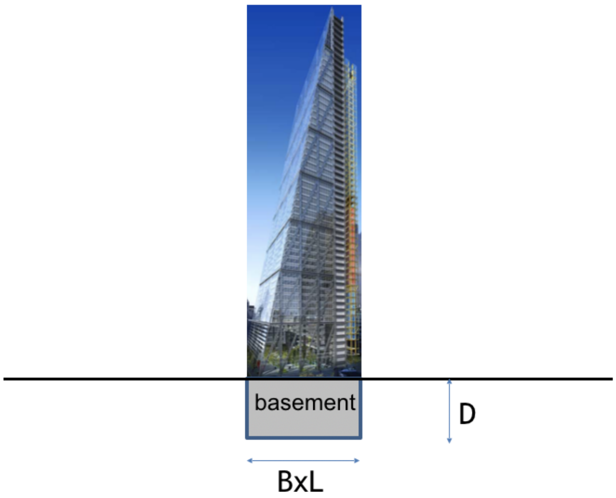
Correction Factor = 1/90

Therefore, the final settlement:

$$P_i = 0.0332/90$$

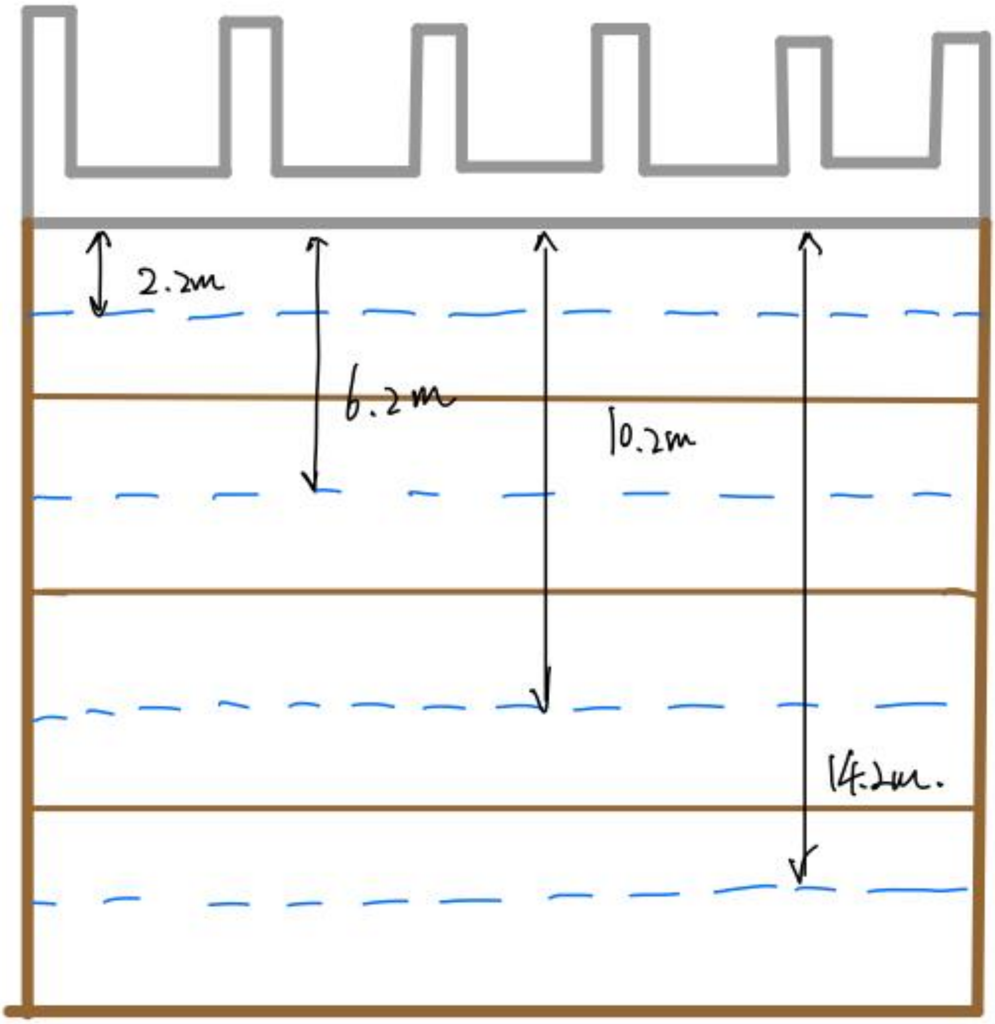
$$\mathbf{P_i = 3.6974 * 10^{-4}\ m}$$





Consolidation Settlements for Non One-Dimensional Loading

In this case, because there is lateral soil movement (not one-dimensional), underneath the structure, the increase of stress will reduce with depth, and at great/infinite depth the stress increases will become insignificant to the settlement. For simplicity, we are dividing the soil into 4 layers and will calculate the stress change $\Delta\boldsymbol{\sigma}$ at the depth of the middle of each layer (Z)



Depth of each layer

- Layer 1 $Z_1 = 2.2$ m
- Layer 2 $Z_2 = 6.2$ m
- Layer 3 $Z_3 = 10.2$ m
- Layer 4 $Z_4 = 14.2$ m

Underneath the structure:

$$\Delta\boldsymbol{\sigma} = \text{Weight W / (Area of the basement A)}$$

Where W = weight of the bridge and foundation = 2767.2039 kN

Then,

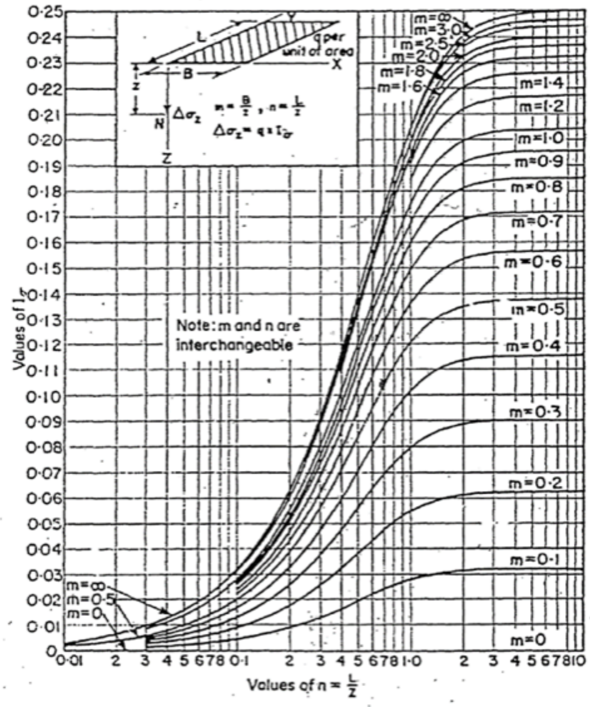
$$\Delta\boldsymbol{\sigma} > \Delta\boldsymbol{\sigma}_1 > \Delta\boldsymbol{\sigma}_2 > \Delta\boldsymbol{\sigma}_3 > \Delta\boldsymbol{\sigma}_4$$

Layers	Area of basement A (m^2)	Change of vertical stress at the foundation $\Delta\sigma$ (kPa)
1	33	1447.5
2	93	513.6
3	153	312.2
4	213	224.3

For rectangular loaded area, the change of vertical stress at depth Z below foundation $\Delta\sigma_z$ for each layer can be calculated by:

$$\Delta\sigma_z = \Delta\sigma * I_\sigma \text{, where}$$

- $\Delta\sigma$ = change of vertical stress at foundation
- I_{σ_corner} = Influence coefficients for the vertical component of stress below the *corner* of a uniformly-loaded rectangular area



The value of corner influence coefficients I_{σ_corner} for each layer can be found be using the diagram on the right:

$$m = (0.5B) / Z \text{ and } n = (0.5L) / Z \text{, where}$$

- B = Breadth of the layer
- L = Length of the layer
- Z = depth of the middle of each layer

By finding the m and n values, we can then find the I_{σ_corner} of each layer. However, we need the central influence coefficients I_σ for settlement calculations, therefore we multiply each I_{σ_corner} value by 4 to find I_σ.

$m_1 = 3.41$, and $n_1 = 6.81$
$0.25*I_{\sigma\_1} = 0.245$
Therefore, $\mathbf{I_{\sigma\_1} = 0.98}$

$m_2 = 1.21$ and $n_2 = 2.42$
$0.25*I_{\sigma\_2} = 0.214$
Therefore, $\mathbf{I_{\sigma\_2} = 0.856}$

$m_3 = 0.73$ and $n_3 = 1.47$
$0.25*I_{\sigma\_3} = 0.169$
Therefore, $\mathbf{I_{\sigma\_3} = 0.676}$
$m_4 = 0.53$ and $n_4 = 1.06$
$0.25*I_{\sigma\_4} = 0.121$
Therefore, $\mathbf{I_{\sigma\_4} = 0.484}$

With the $\Delta\sigma$ and I_σ values, we can calculate the $\Delta\sigma_z$ of each layer:
Because $\Delta\sigma_z = \Delta\sigma * I_\sigma$,

$$\Delta\sigma_{z1} = 39.949342 * 0.98 = \mathbf{39.15}$$
$$\Delta\sigma_{z2} = 39.949342 * 0.856 = \mathbf{34.197}$$
$$\Delta\sigma_{z3} = 39.949342 * 0.676 = \mathbf{27.006}$$
$$\Delta\sigma_{z4} = 39.949342 * 0.484 = \mathbf{19.335}$$

Using the initial effective vertical stress equation from previous sections, we find the initial vertical stress σ'_{v0} for each layer; By adding σ'_{v0} and $\Delta\sigma_z$, we can find the final effective vertical stress $\sigma'vf$. With the stress values, the initial and final void ratios can be found by using the void ratio-vertical stress graph again.

The equation $p_c = H_i * (e_0 - ef)/(1 + e0)$ can be used to find the settlements of each layer; In this case, Hi is the depth of each layer (Z).

Layers	Depth (m)	σ_{v0}(kPa)	$\Delta\sigma_z$(kPa)	σ_{vf}(kPa)
1	2.2	216.028	39.15	255.178
2	6.2	256.788	34.197	290.985
3	10.2	286.452	27.006	324.554
4	14.2	325.692	19.335	357.643

<u>Calculations</u>

Layer 1
- e_0 for layer 1 = 0.734 (from the gradient of graph)
- e_f =0.723
- Z_1 = 2.2m

Therefore, p_{c1} = 0.0147

Layer 2
- e_0 = 0.726
- e_f=0.703
- Z_2 = 6.2m

Therefore, p_{c2} = 0.0665

Layer 3
- e_0 = 0.6997
- e_f = 0.685
- Z_3 = 10.2m
- Therefore, p_{c3} = 0.0875

Layer 4

- e_0 = 0.678
- e_f =0.667
- Z_4 = 14.2m

Therefore, p_{c4} = 0.0884

Layers	e_0	e_f	p_c (m)
1	0.734	0.723	0.0147
2	0.726	0.703	0.0665
3	0.6997	0.685	0.0875
4	0.678	0.667	0.0884
Total	/	/	0.2571

As a result, the total consolidation settlement is the sum of p_c of the 4 layers, which is

$$\mathbf{p_c = 0.2571\ m}$$

Therefore, the drained settlement would be

$$p_d = p_i + p_c$$

$$\mathbf{p_d = 0.2903\ m}$$

Correction of $\Delta\sigma$

Again, because the loading is not one-dimensional, we would have to calculate a corrected value of the total settlement.

The correction factor equation is

$$\Delta\sigma_{corrected} = u * \Delta\sigma \text{ for each layer}$$

For London clay and for a typical foundation geometry, it would be reasonable to choose a u value of 0.5 (according to the slides).

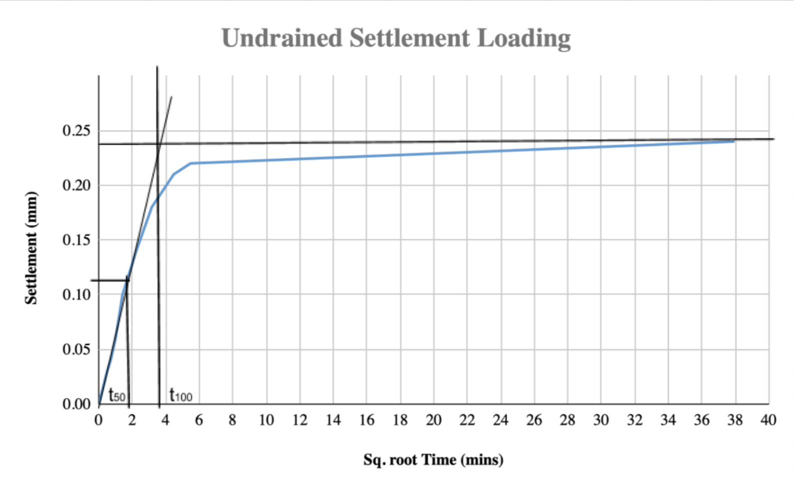
$\Delta\sigma_{corrected\_1}$	19.575 kPa
$\Delta\sigma_{corrected\_2}$	17.0985 kPa
$\Delta\sigma_{corrected\_3}$	13.503 kPa
$\Delta\sigma_{corrected\_4}$	9.668 kPa
Total $\Delta\sigma_{corrected}$	59.8 4kPa

Therefore, the total **Δσcorrected = 59.84 kPa**.

Time for Consolidation Settlement

We are assuming the soil in the ground is a giant oedometer/ 1D conditions as it is better just to do this simple calculations for an idea of the order of magnitude.

Since full consolidation takes infinite time, we will calculate a time for a proportion of the settlement to occur -- t_{50}.



We are assuming that dense sandy gravel and other permeable materials are below the clay layer and therefore drainage path length H will be the half of the sample height.

By using a settlement-√time graph (from an oedometer for London clay), we can find the time for half the settlement to occur in an oedometer. From the graph, we assume that the total settlement p_∞ is 0.24

Gradient of the graph = 0.0626
So p (settlement)=0.0626 * t,
when half of the settlement ($p_\infty/2$) = 0.24/2 = 0.12,
T = 1.917 min

Clay depth (H) ranges from 8 m to 30 m below the surface. This gives a soil layer depth of 22 m.
H = 11000 mm
H^2 = 121 000 000 mm

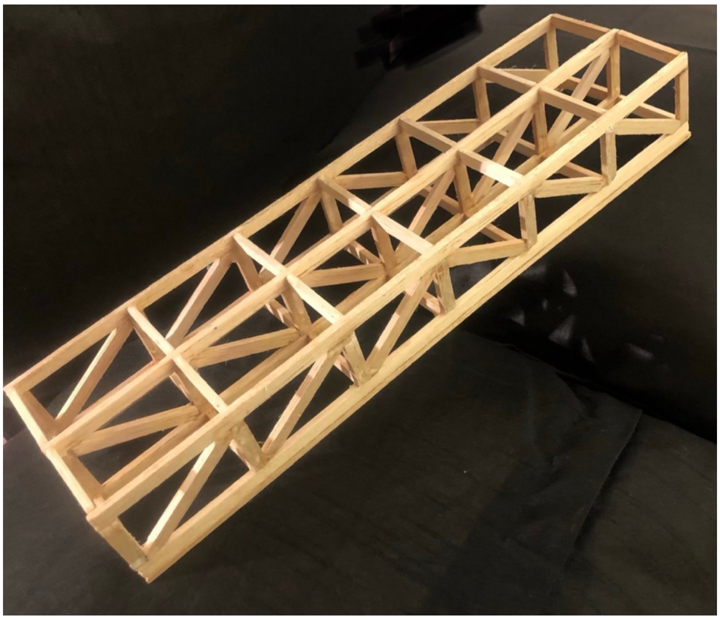
For the case of an oedometer, the initial sample height 20.12 mm
H = 10.06 mm
H^2 = 101.2036 mm
ratio=101.2036 / 121000000 = $8.364*10^{-7}$

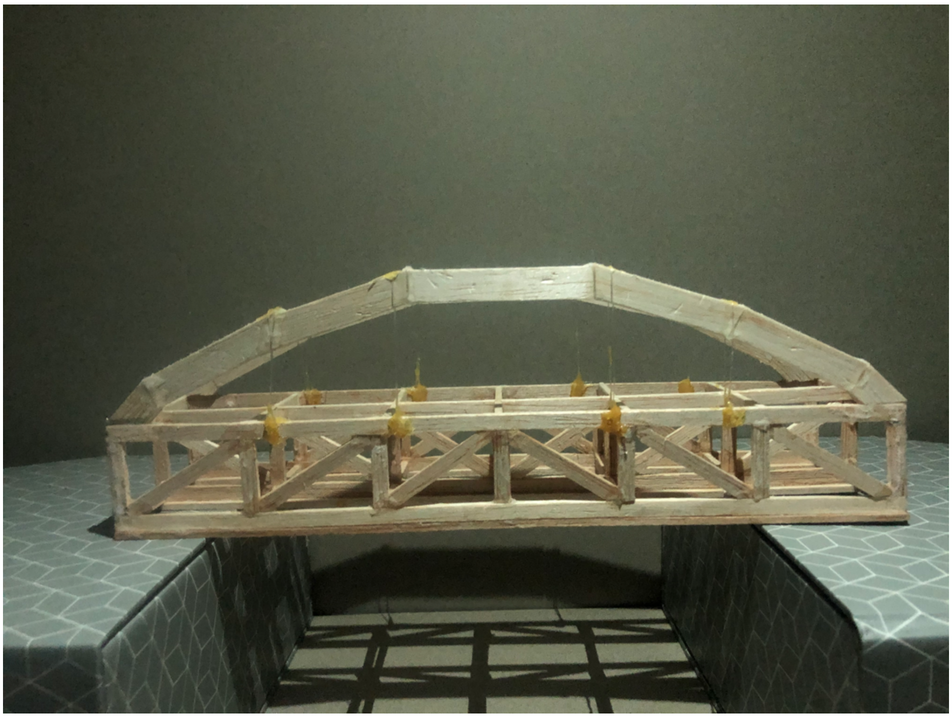
Therefore, t50 can be calculated:
t50 = 1.917min / ($8.364*10^{-7}$)
t50 = 2291965.567 min
t50 = 4.42 years for half the settlement to take place

MODEL TESTING

We have decided to focus on one final model rather than testing simpler versions as we had found a form that would represent the bridge properly and we were sure we could sustain a significant weight on the structure. This is due firstly to the trusses that constitute the deck resulting in a very stable base, as well as the cables under tension that add stability to the arch and whole structure. Also, we made sure that the direction of use of the balsa wood would have a higher moment of inertia, therefore resisting buckling.

Construction Process:





The weight of the model is 40g.

The materials used are:

- Balsa wood
- Plastic Strings
- Gorilla glue
- Hot glue

Items weighed (check video for proof):

<u>First loading (till 5kg limit)</u>

x1 Steel chain = 150 g
x10 500 mL bottles of water = 534g each

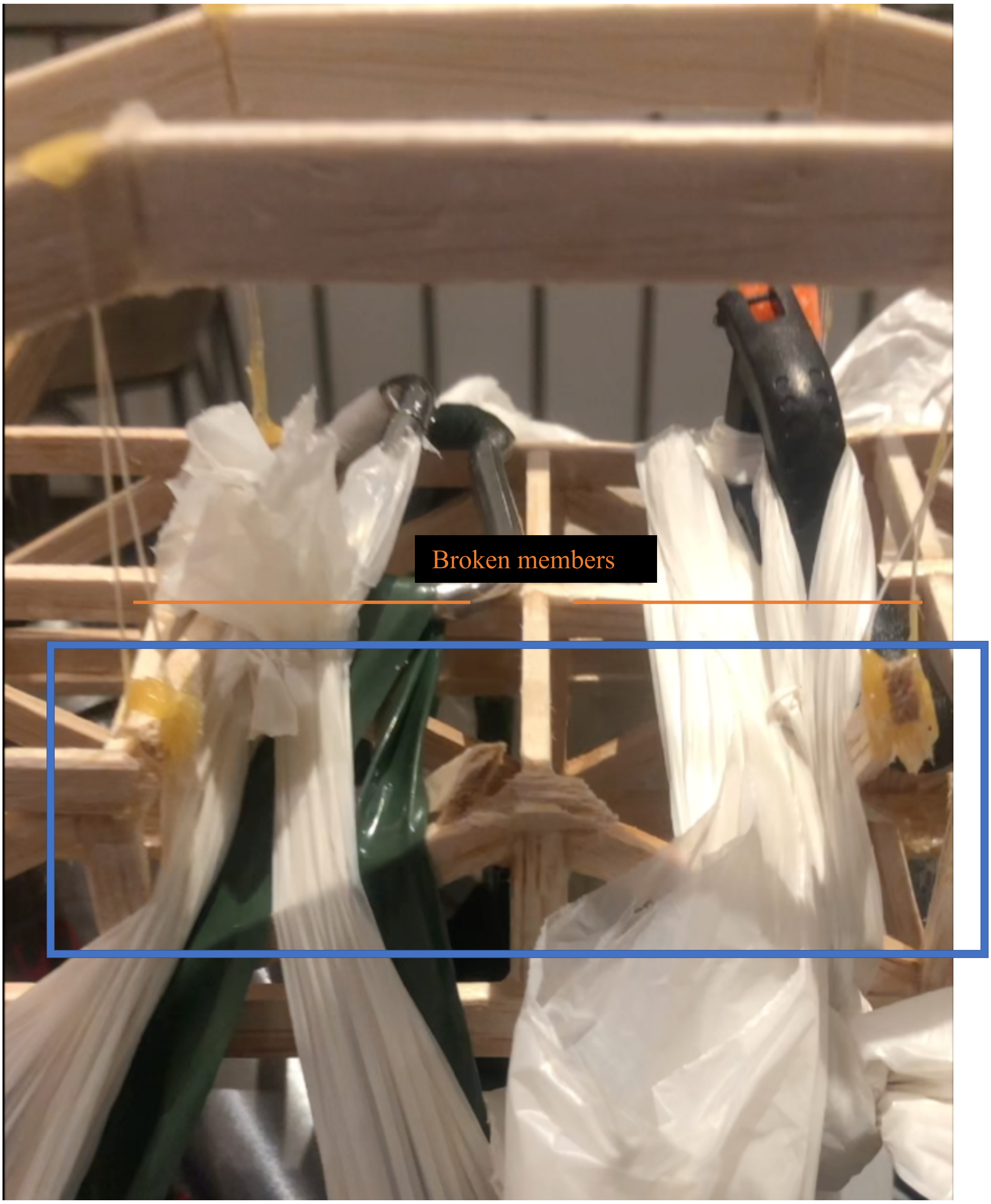
➔ The structure was able to support 5335 g without failing

<u>Second loading (loading till failure)</u>

x11 500 mL bottles of water = 534g each
x1 Liquid Soap = 830g
x1 Stainless steel bottle (filled) = 924 g
x5 Bags of rocks = approx. 4kg each
x2 Small coffee tables >=5 kgs each (could not determine with the scale given)

➔ Minimum weight carried = 37.6 kg before failure

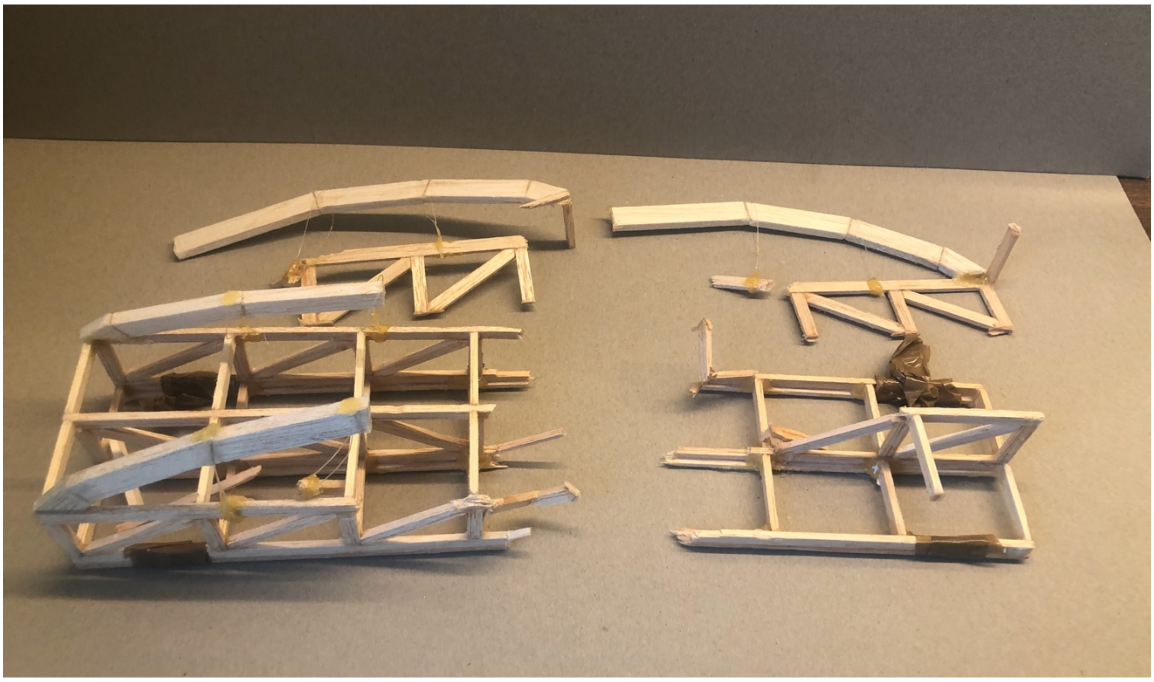
The first sign of breaking was the horizontal element of the truss on which the weighs lied on. Even after the member breaking, the structure still supported the weight. This is due to a redistribution of the load to the other members of the truss.

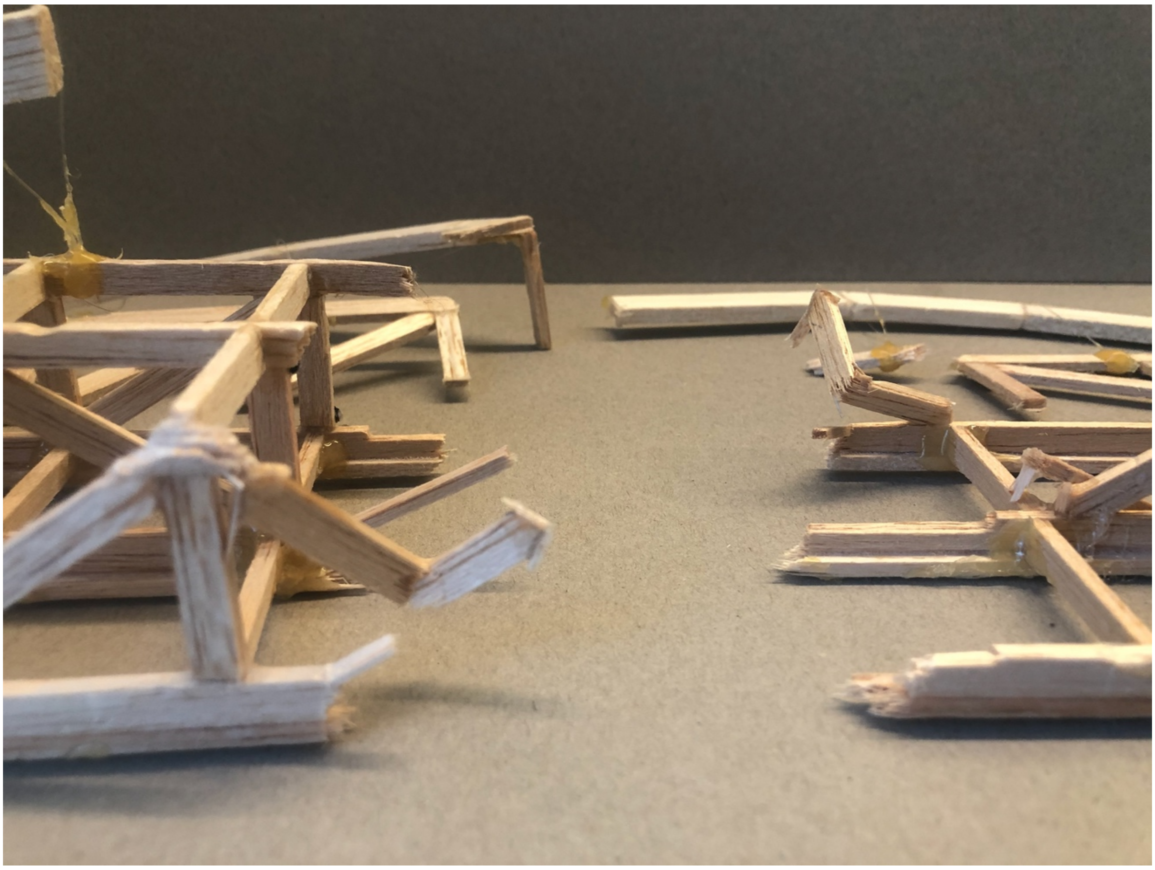

Broken members

When adding additional load onto that, the parallel horizontal element broke as well, however the structure remained standing.

After trying to move the weight, it took a minute for the whole structure to collapse (appearing as shorter on the video due to time-lapse).

Failure of the structure:





The number of materials used was optimized and every component of the structure has an essential supporting function. Perhaps one aspect that could have been improved is the height of the trusses. Reducing their height would optimize the number of materials used without affecting the design of the bridge.

After observing the significant weight that the model was able to hold without breaking and comparing it to the weakness of the material used, we notice the importance of the structural configuration of the bridge. Thus, this model has confirmed our intentions of providing extra support to the bridge, using different kinds of supporting elements (trusses and cables) to withstand the load. As during the past many designs have underestimated the load that the bridge will be carrying, we aimed to create a bridge that will stand the passing of time and bear significant loads even if unexpected.

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