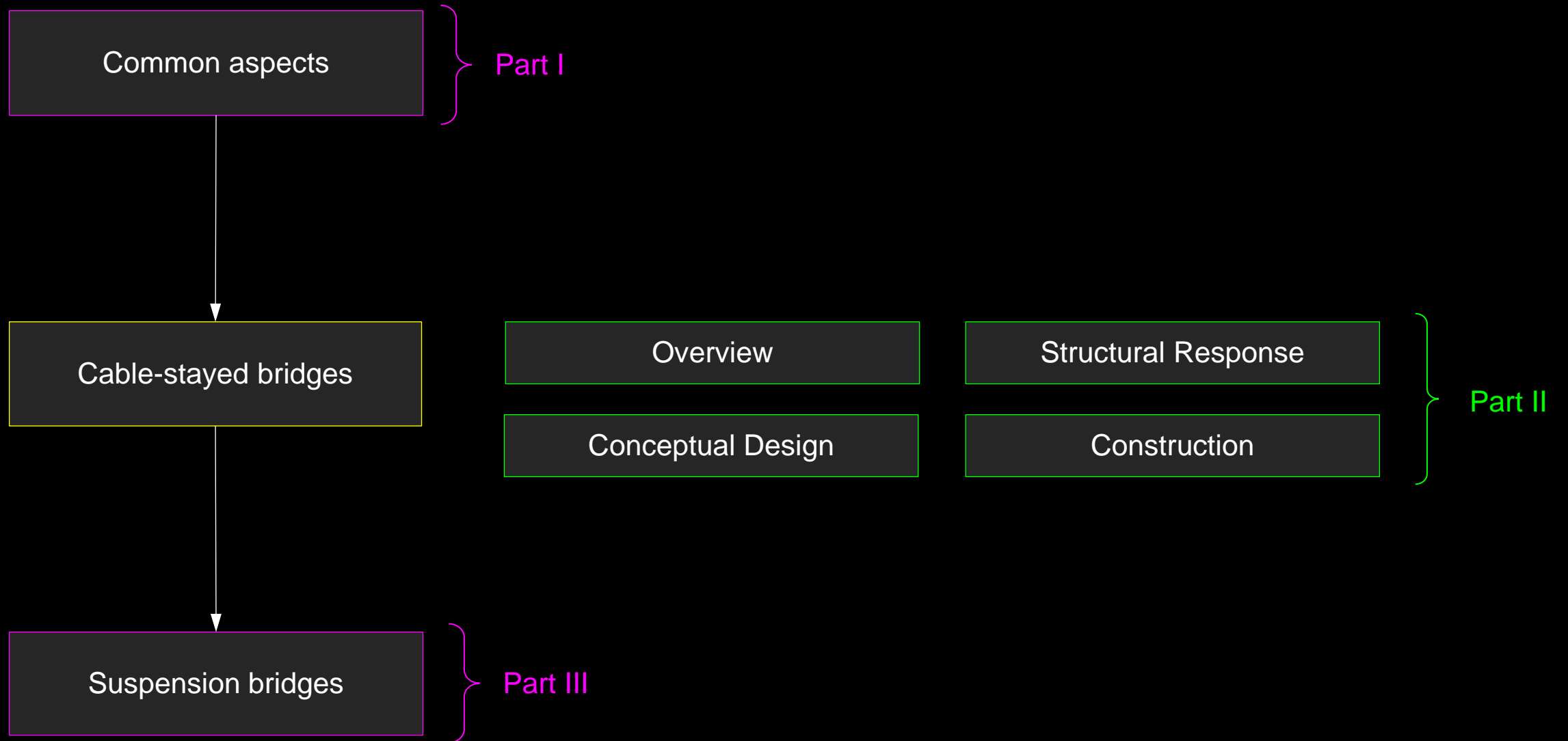


Cable-Stayed Bridges

(Schrägseilbrücken)



Why study cable-supported bridges?

- Basic knowledge of the fundamental behaviour and construction methods of all bridge typologies is required at the conceptual phase
- For engineers seeking to specialise in long-span bridges → starting point...
- For engineers indirectly involved in long-span bridges, e.g. as Owner, Prime consultant → develop a common language and understanding of the key issues involving long-span bridges

Learning objectives:

- What is the fundamental **behaviour** of cable-stayed bridges?
- What are the main **geometric features** of cable-stayed bridges and which design requirements determine their form?
- When is a cable-stayed bridge the **appropriate typology** and how does it compare with competing typologies?
- What are some of the **particularities** of cable-stayed bridges?
- What are the main considerations with respect to **constructibility**?

Cable-supported bridges

Cable-stayed bridges – Overview

Cable-supported bridges – Cable-Stayed Bridges: **Overview**

Forth Rail Bridge

Construction: 1882 – 1890

(73 lives lost)

Total length = 2'467 m

Longest span = 520 m

Width = 9.8 ... 37 m

Height = 110 m

Forth Road Bridge

Construction: 1958 – 1964

(7 lives lost)

Total length = 2'512 m

Longest span = 1'006 m

Width = 33 m

Height = 156 m

Queensferry Crossing

Construction: 2011 – 2017

(1 life lost)

Total length = 2'700 m

Longest span = 650 m

Width = 40 m

Height = 207 m

Cable-supported bridges

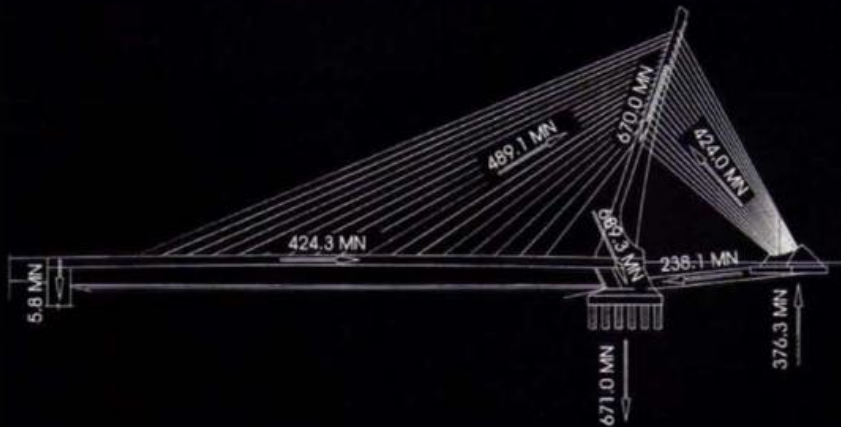
Cable-stayed bridges – Overview Definition and Classification

Cable-supported bridges – Cable-Stayed Bridges: **Overview**

- Cable-Stayed Bridges can be classified by:

→ **Span Arrangement:**

- Single Span
- Two Span
- Three Span (standard)
- Multi Span

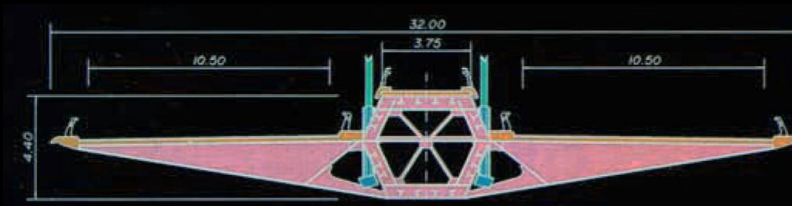
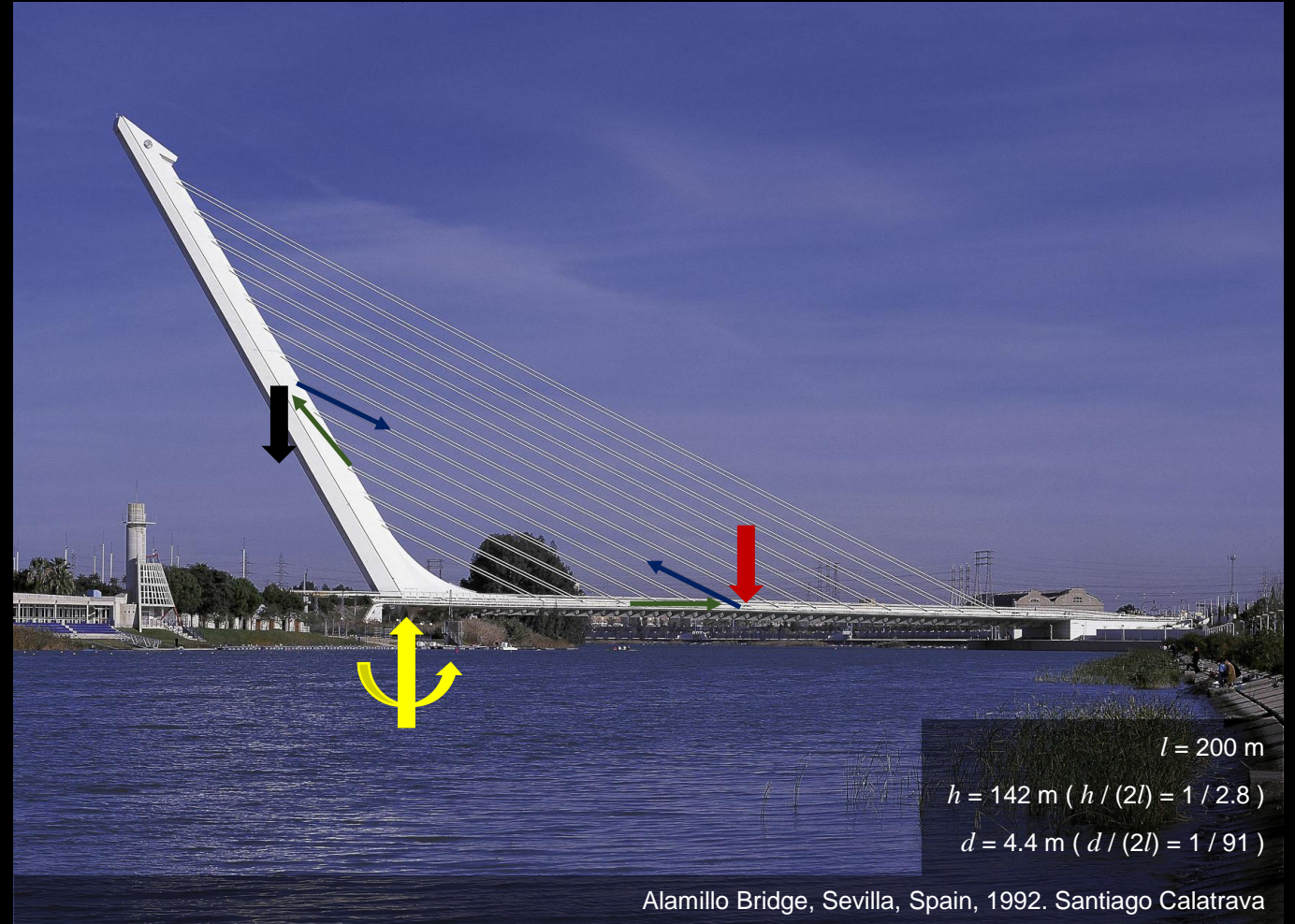


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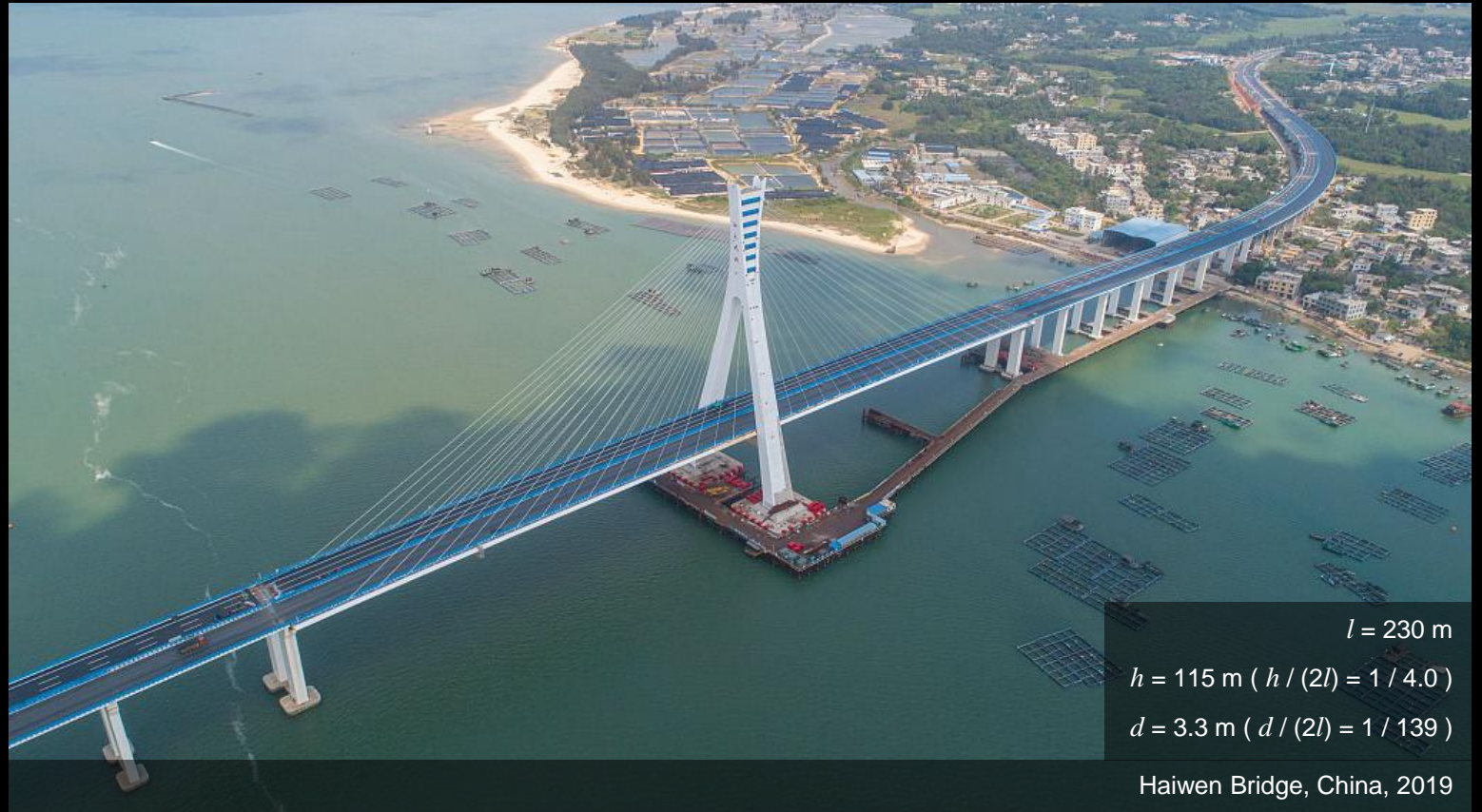


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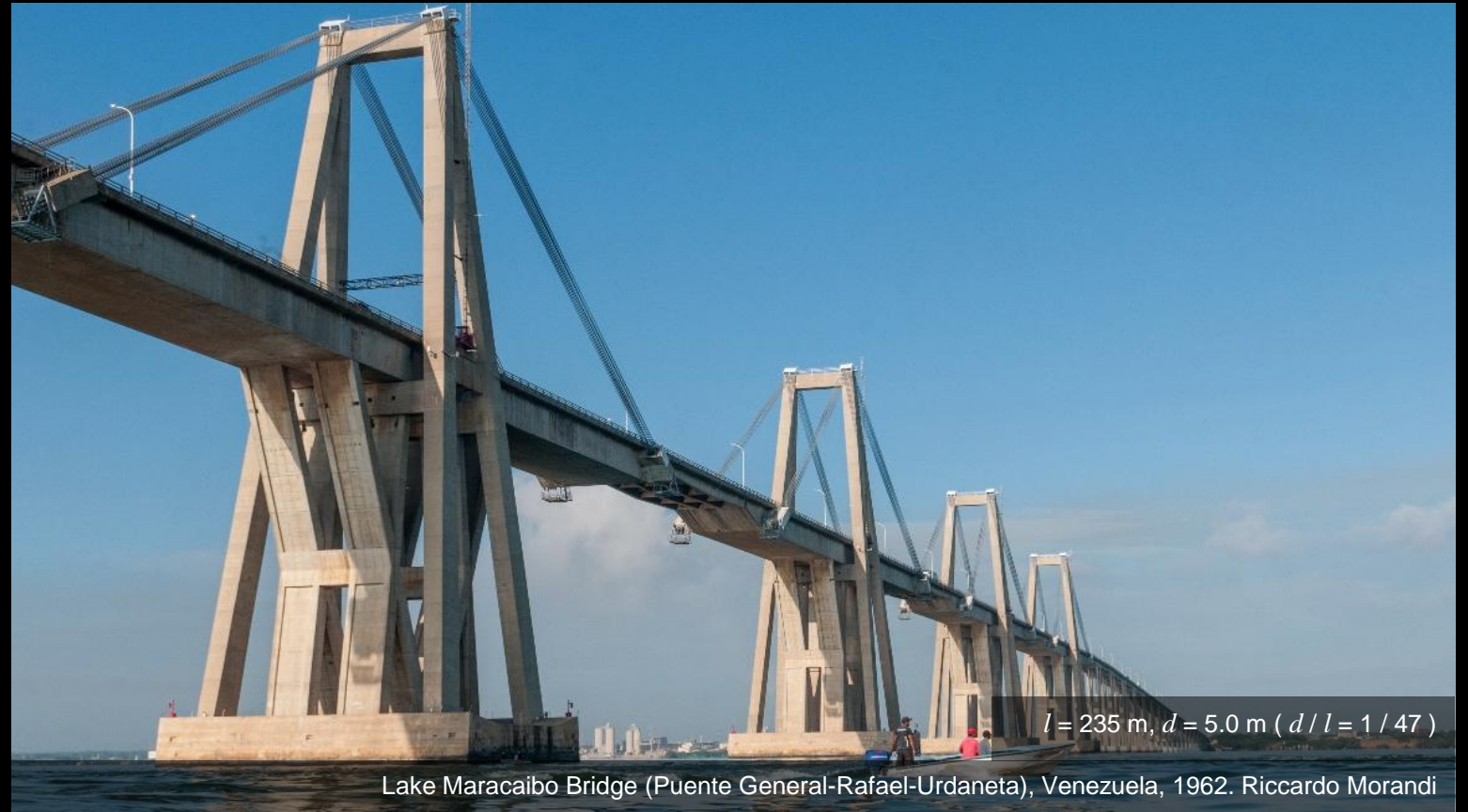
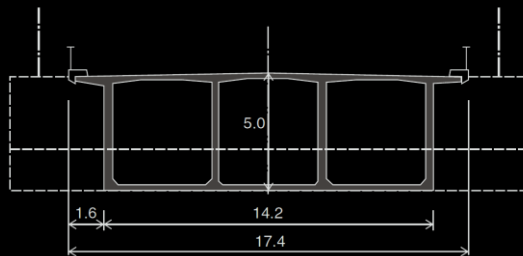


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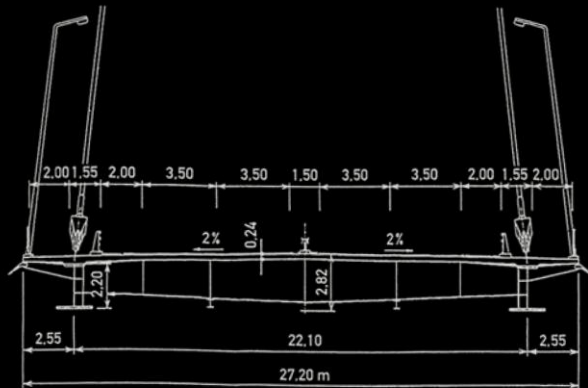


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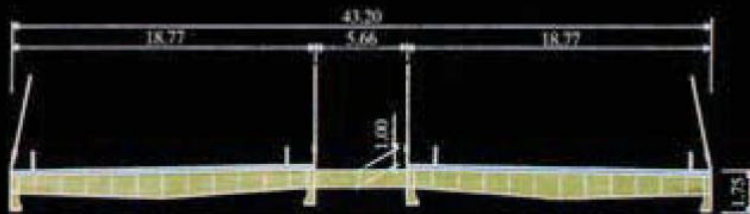


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Cable-supported bridges – Cable-Stayed Bridges: **Overview**

- Cable-Stayed Bridges can be classified by:

- **Span Arrangement:**

- Single Span
- Two Span



$l = 650 \text{ m}, l_1 = 221+104 \text{ m} (l_1 / l = 0.50)$

$h = 145 \text{ m} (h / l = 1 / 4.5)$

$d = 4.8 \text{ m} (d / l = 1 / 135)$



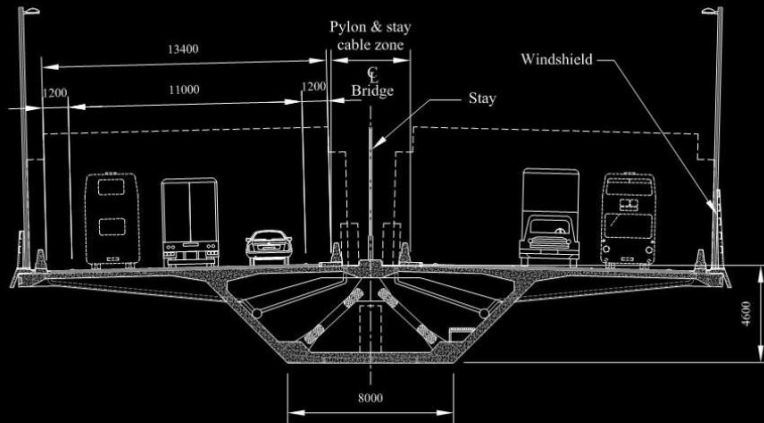
Queensferry Crossing, Queensferry, UK, 2017. Jacobs / Arup

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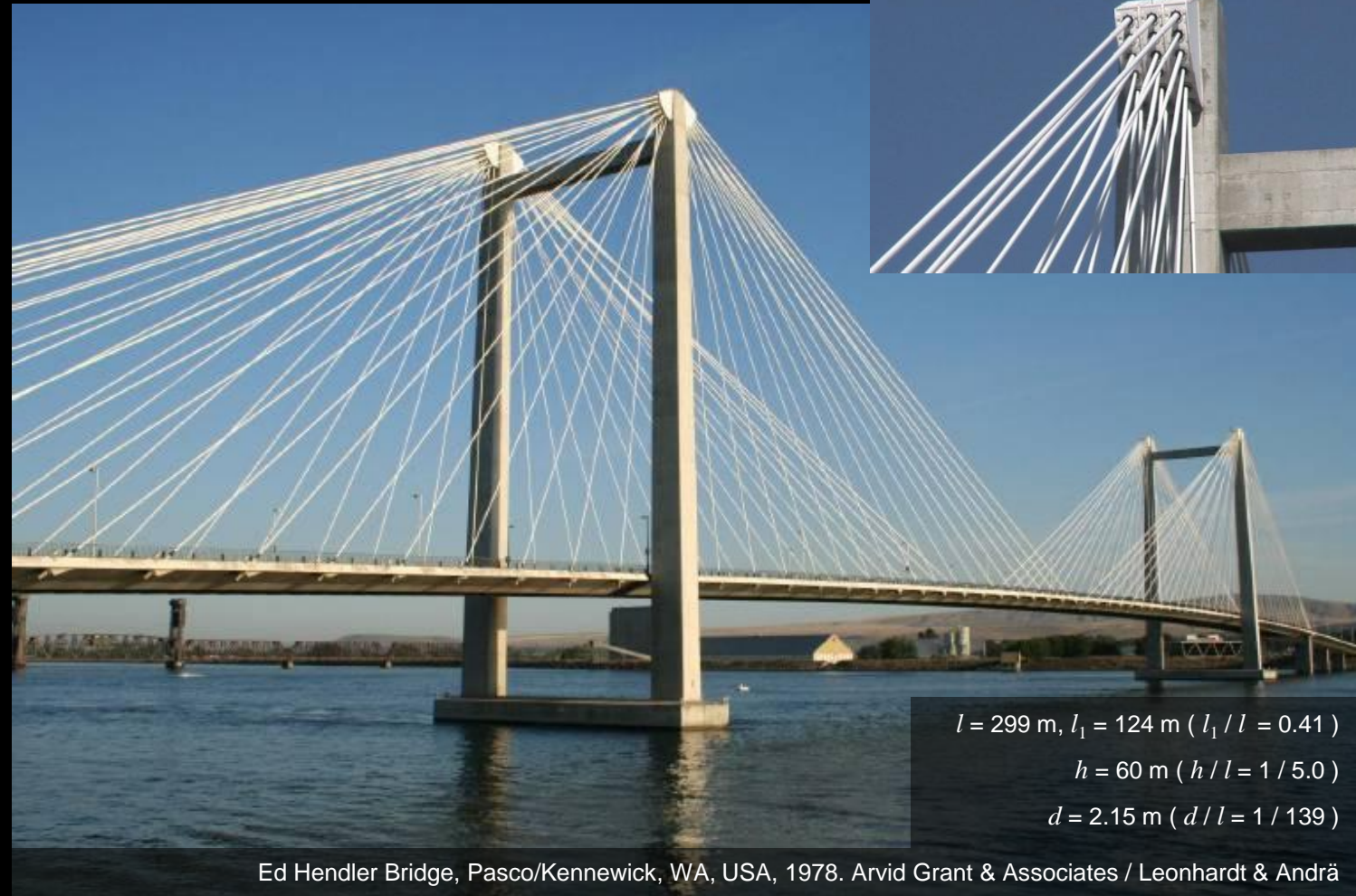
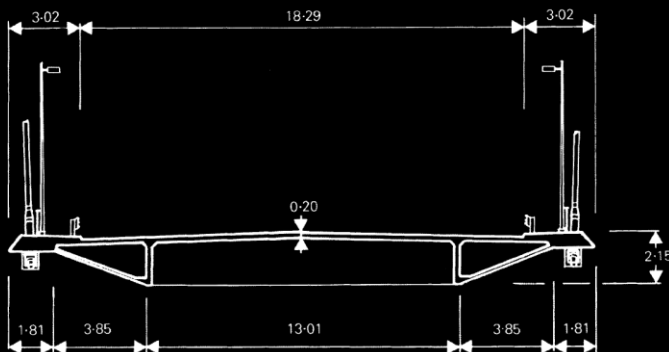


Cable-supported bridges – Cable-Stayed Bridges: **Overview**

- Cable-Stayed Bridges can be classified by:

→ Stay Cable Arrangement:

- Fan
- Harp
- Hybrid (Semi-Fan)



$$\begin{aligned} l &= 299 \text{ m}, l_1 = 124 \text{ m} \quad (l_1 / l = 0.41) \\ h &= 60 \text{ m} \quad (h / l = 1 / 5.0) \\ d &= 2.15 \text{ m} \quad (d / l = 1 / 139) \end{aligned}$$

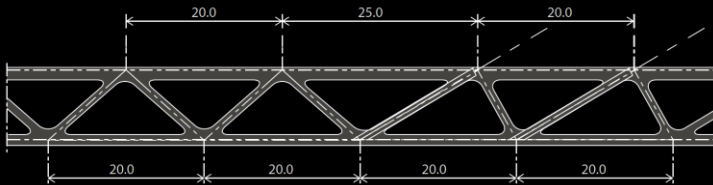
Ed Hendler Bridge, Pasco/Kennewick, WA, USA, 1978. Arvid Grant & Associates / Leonhardt & Andrä

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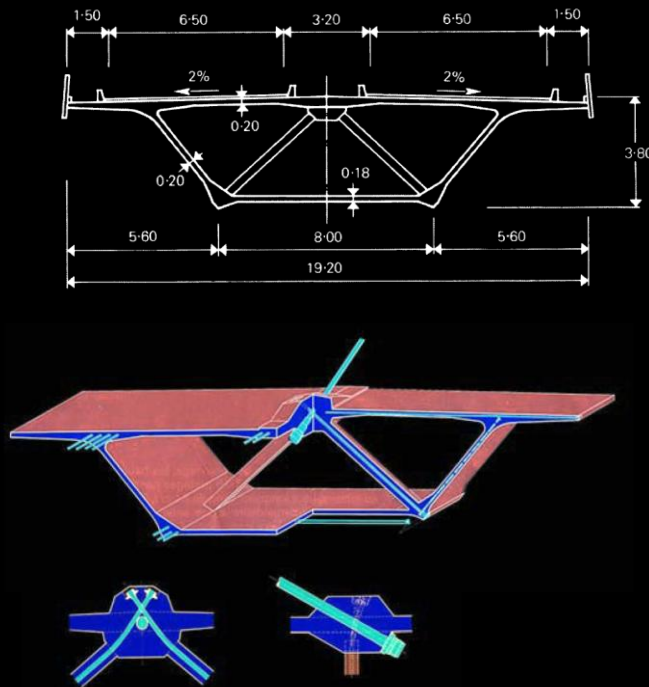


Cable-supported bridges – Cable-Stayed Bridges: **Overview**

- Cable-Stayed Bridges can be classified by:

→ Stay Cable Planes:

- Single Plane
- Two Vertical Planes
- Two Inclined Planes



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- Two Vertical Planes
- Two Inclined Planes
- Multiple Vertical Planes
- Multiple Inclined Planes

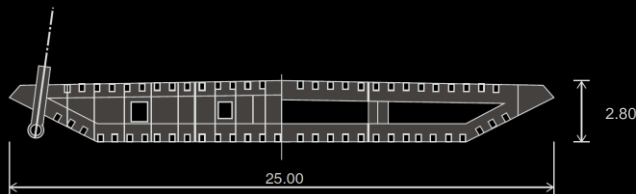


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- Two Vertical Planes
- Two Inclined Planes
- Multiple Vertical Planes
- Multiple Inclined Planes



$l = 190 \text{ m}, l_1 = 95 \text{ m} \ (l_1 / l = 0.50)$

$h = 42 \text{ m} \ (h / l = 1 / 4.5)$

$d = 1.7 \dots 3.7 \text{ m} \ (d / l = 1 / 113 \dots 1 / 52)$

Pitt River Bridge, Vancouver, BC, Canada, 2009. IBT

Cable-supported bridges – Cable-Stayed Bridges: **Overview**

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Cable-supported bridges – Cable-Stayed Bridges: **Overview**

- Cable-Stayed Bridges can be classified by:

→ Tower Configuration:

- Single Tower
- “H” Tower
- “A” Tower
- Diamond Tower
- Double Diamond Tower
- Inverted “Y” Tower

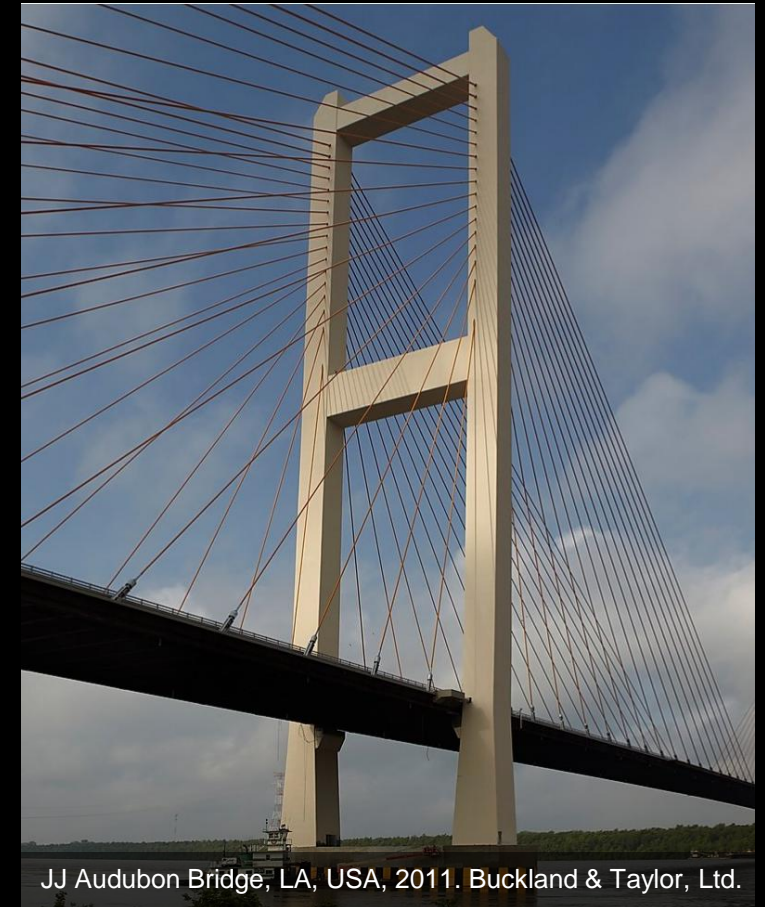
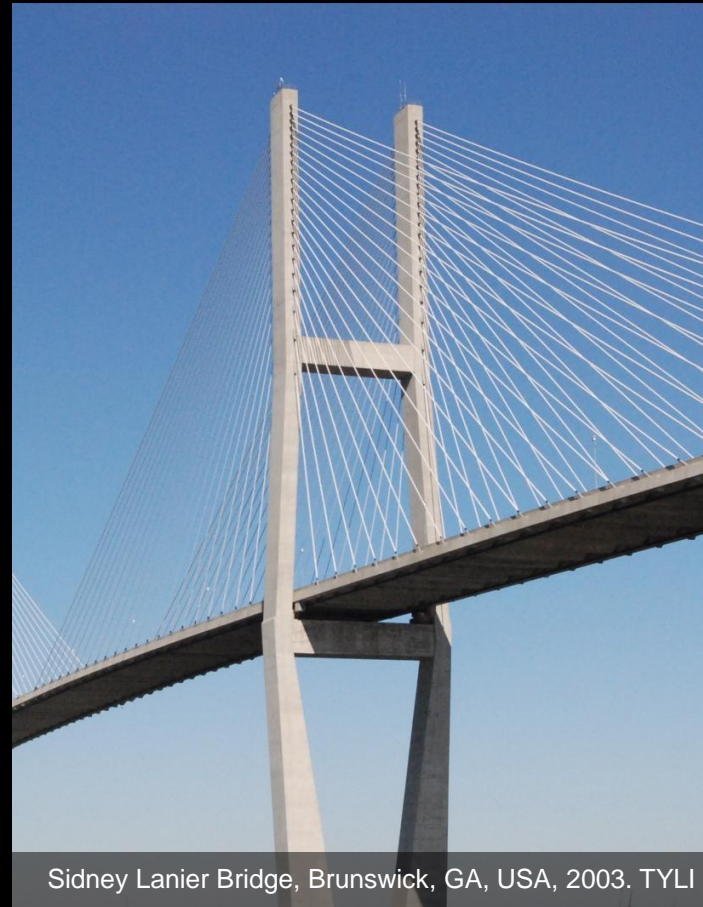


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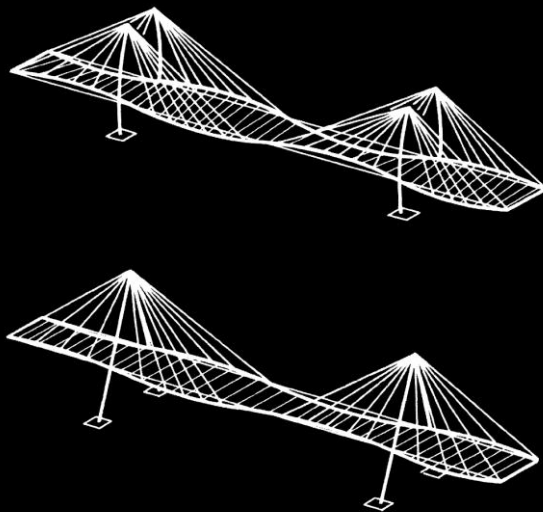


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$l = 405 \text{ m}, l_1 = 176.5 \text{ m} \ (l_1 / l = 0.44)$

$h = 85 \text{ m} \ (h / l = 1 / 4.8)$

$d = 2.8 \text{ m} \ (d / l = 1 / 145)$

Second Meiko Nishi Bridge, Nagoya, Japan, 1997

Cable-supported bridges – Cable-Stayed Bridges: **Overview**

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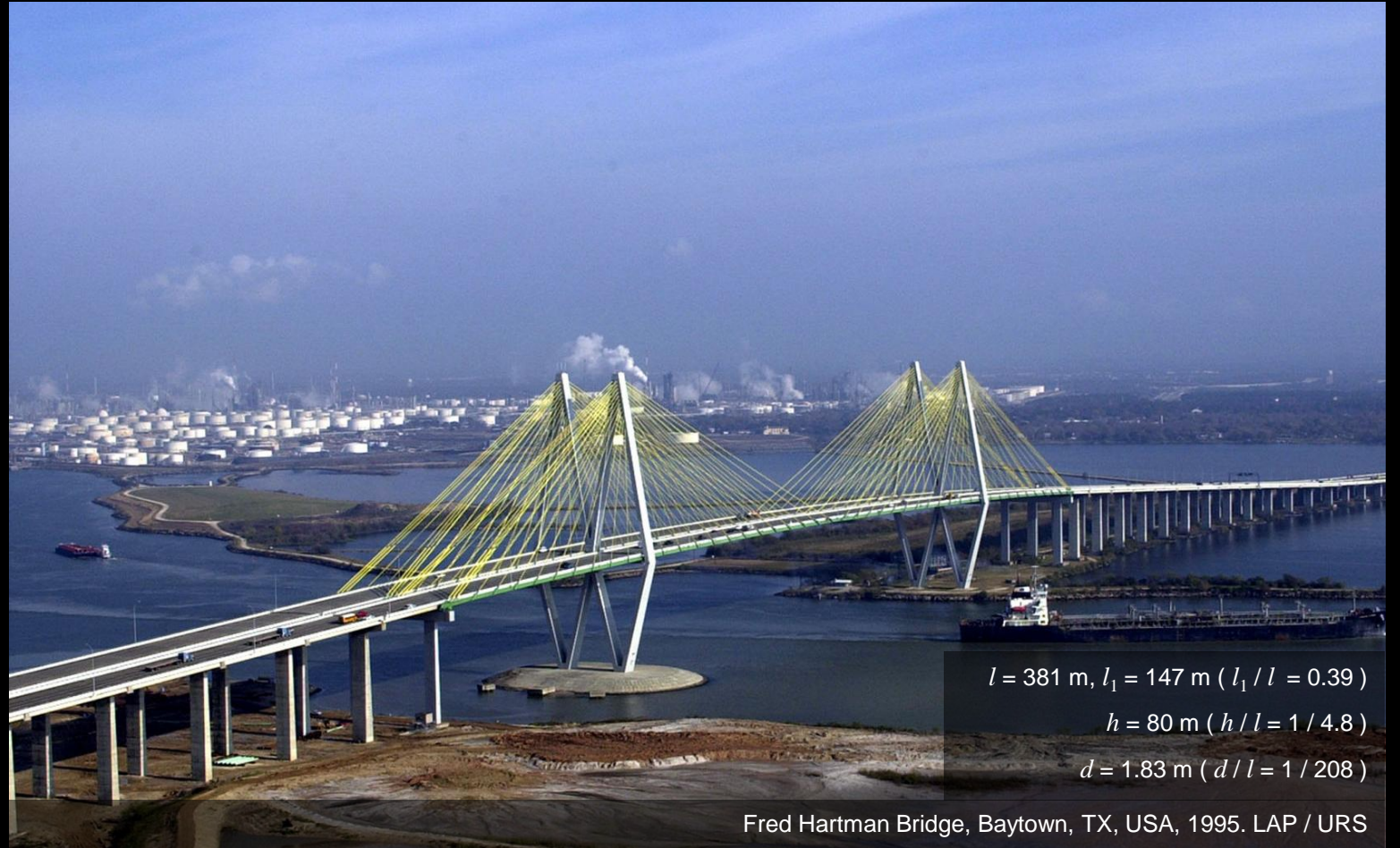
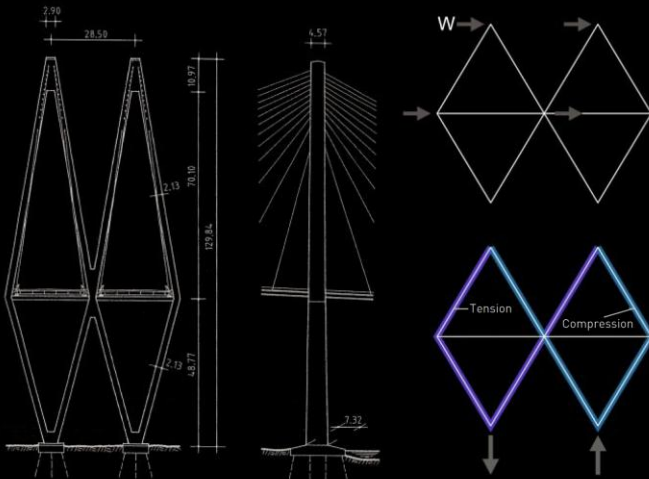
Arthur Ravenel Jr. (Cooper River) Bridge, SC, USA, 2005. Parsons Brinkerhoff Quade & Douglas

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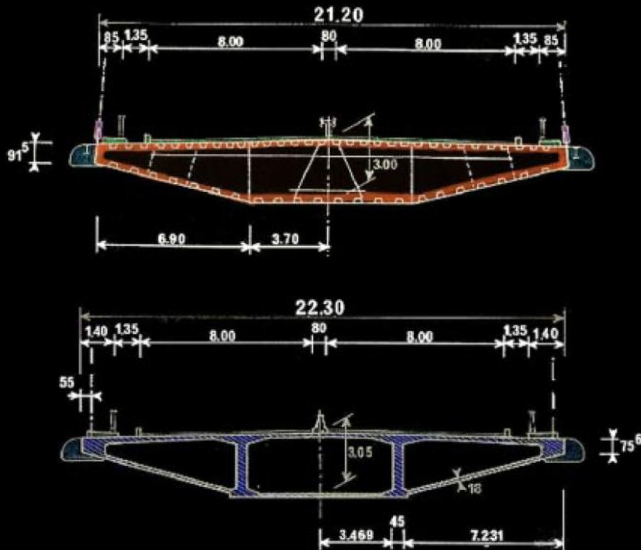


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$$l = 856 \text{ m}, l_1 = (96 + 5.5 \times 43.5) \text{ m} \quad (l_1 / l = 0.39)$$

$$h = 155 \text{ m} \quad (h / l = 1 / 5.5)$$

$$d = 3.0 \text{ m} \quad (d / l = 1 / 285)$$

Pont de Normandie, France, 1995. Michel Virlogeux

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Cable-supported bridges – Cable-Stayed Bridges: **Overview**

- Cable-Stayed Bridges can be classified by:

→ **Girder Type:**

- Flexible
 - Concrete Edge Girder
 - Steel / Composite Edge Girder
 - Hybrid: Concrete Edge Girder + Steel Floor Beams
- Stiff
 - Concrete Box
 - Steel Box (Orthotropic)
 - Truss



Sidney Lanier Bridge, Brunswick, GA, USA, 2003. TYLI

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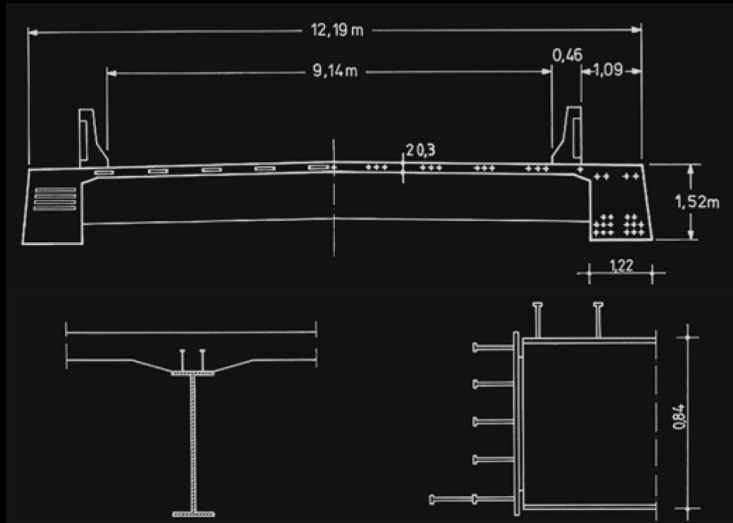


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East Huntington Bridge, WV, USA, 1985. Arvid Grant / LAP

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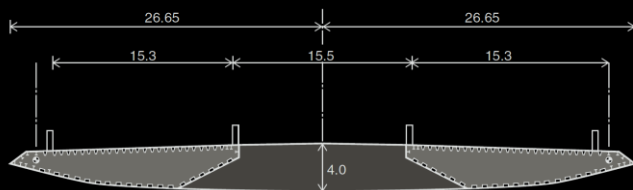
Brotonne Bridge, Normandy, France, 1977. Jean Muller

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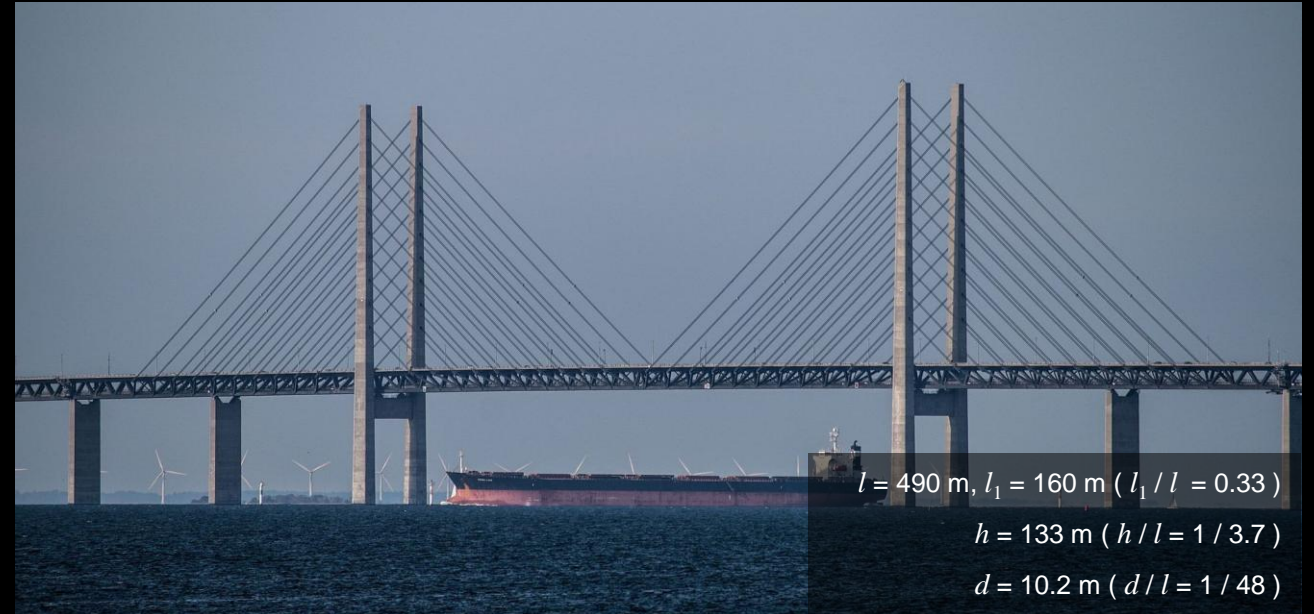
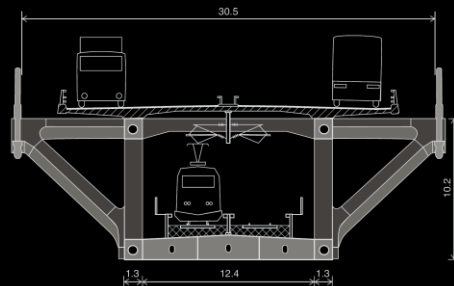
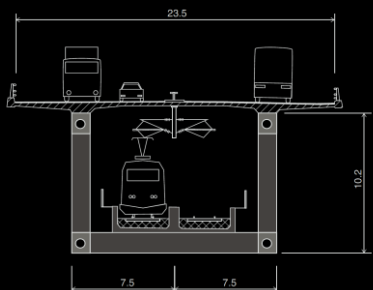


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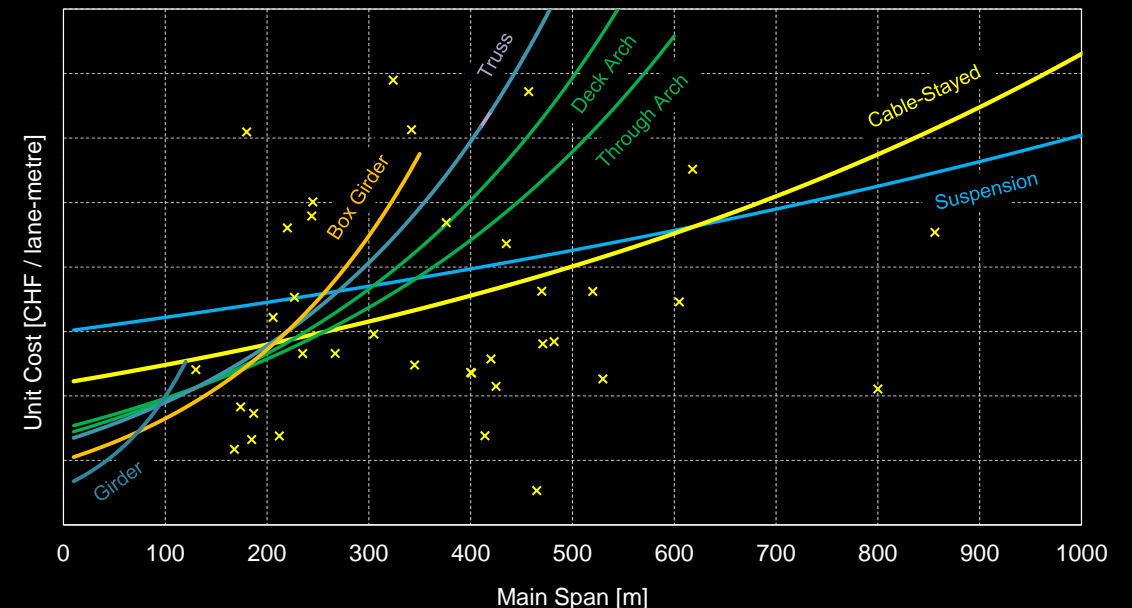
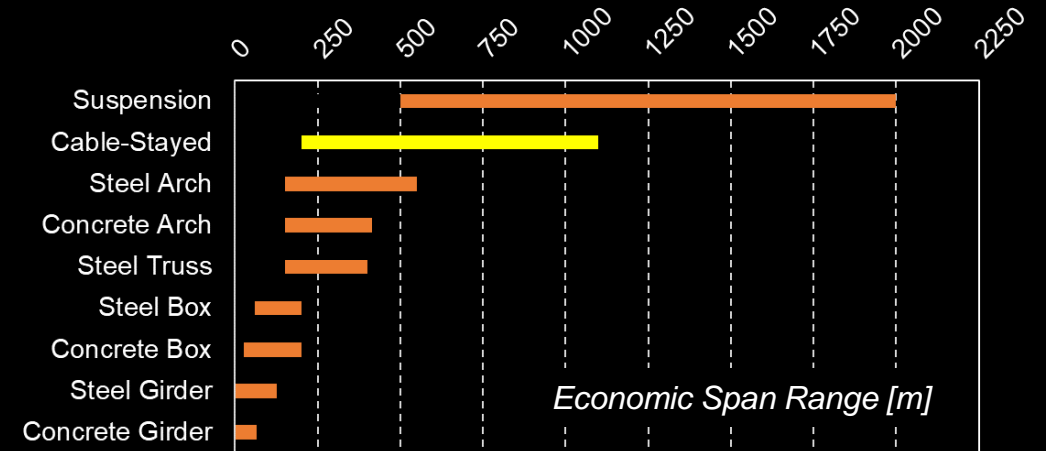


Cable-supported bridges

Cable-stayed bridges – **Conceptual Design**

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

- Planning and bridge concept selection:
 - Cable-stayed bridges have become the most **competitive** bridge typology for a **wide range** of spans (200 ... 1100 m)
 - For very long spans (> 500 m) the only other alternative are **suspension** bridges
 - For medium to long spans (200 ... 500 m) there are **several competing typologies**, typically at a higher unit cost though
 - For short to medium spans (< 200 m) **girder** bridges are usually more economical than cable-stayed bridges
 - The area where the curves intersect (~ 200 m) is of great interest



Cable-supported bridges – Cable-Stayed Bridges: **Conceptual Design**

main span = 304 m; total length = 481 m
width = 14.2 m (2-lane roadway)
pylon height = 142 m; clearance below = 49 m



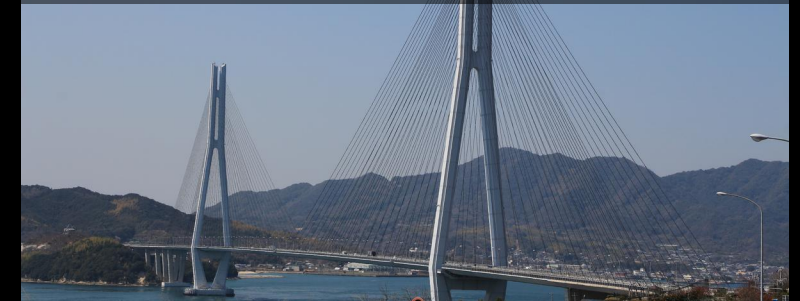
Franjo Tuđman Bridge, Croatia, 2002, University of Zagreb.

main span = 1018 m; total length = 1596 m
width = 51 m (6-lane roadway)
pylon height = 298 m; clearance below = 73 m



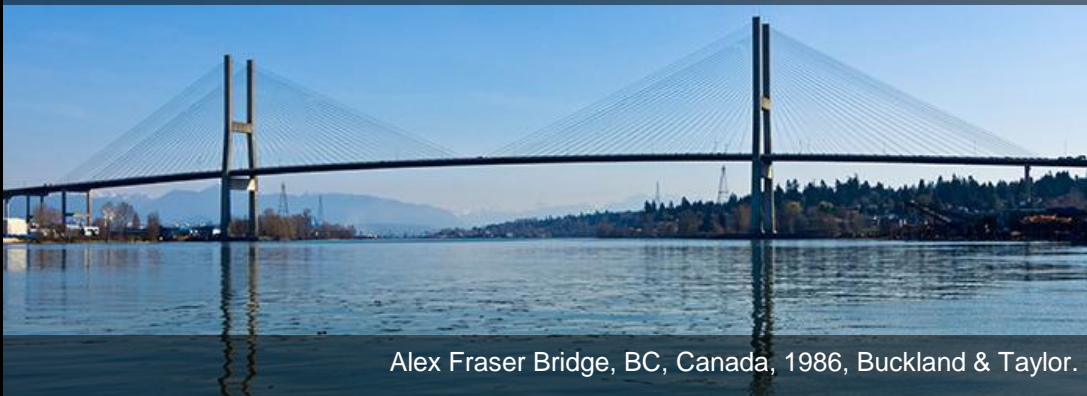
Stonecutters Bridge, HK, 2009. Arup / COWI

main span = 890 m; total length = 1480 m
width = 30.6 m (4-lane roadway)
pylon height = 220 m; clearance below = 26 m

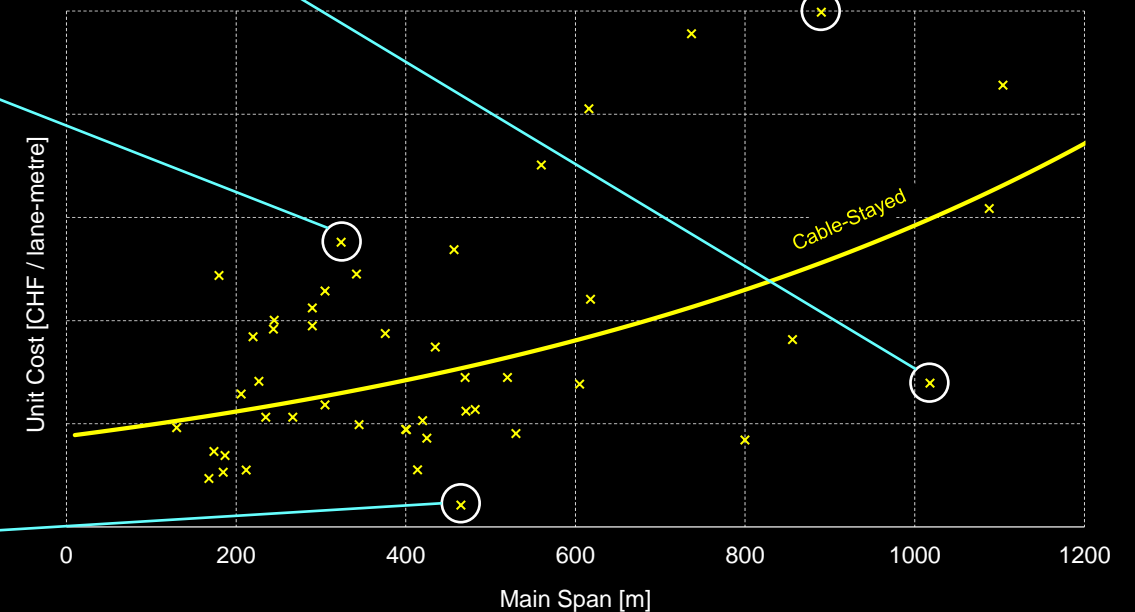


Tatara Bridge, Japan, 1999. Honshu-Shikoku Bridge Authority

main span = 465 m; total length = 930 m (2525 m incl. approaches*)
width = 32 m (7-lane roadway)
pylon height = 154 m; clearance below = 57 m



Alex Fraser Bridge, BC, Canada, 1986, Buckland & Taylor.



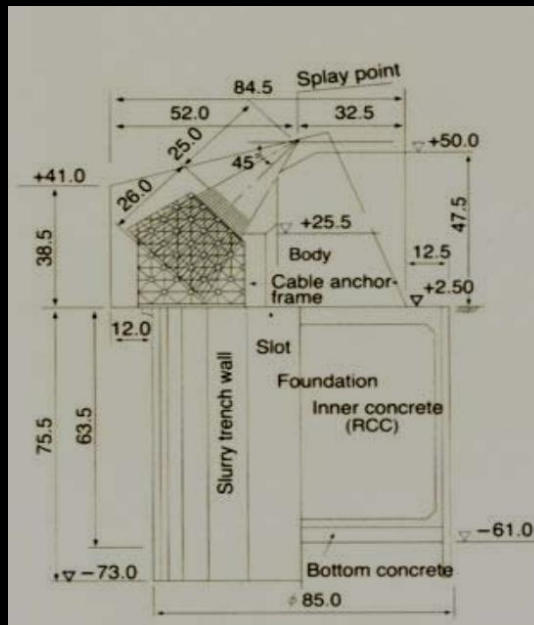
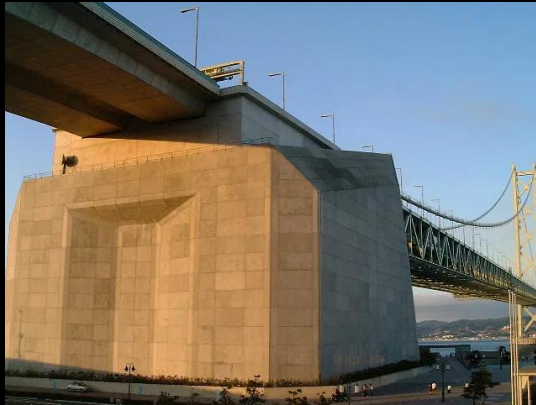
Cable-supported bridges – Cable-Stayed Bridges: **Conceptual Design**

- Planning and bridge concept selection:
 - Cable-stayed bridges have become the most competitive bridge typology for a wide range of spans (200 ... 1100 m)
 - For very long spans (**> 500 m**) the only other alternative are **suspension** bridges
 - Main disadvantages of **suspension bridges vs. cable-stayed bridges** are:
 - **Construction time**: Suspension cable spinning is a lengthy process (even if PPWS are used), while erection of stay-cables is faster and concurrent with deck erection
 - **Earth anchorages** of suspension cables are massive, while the horizontal component of stay-cable forces is resisted by the deck.
 - **Cable quantity**: Suspension bridges generally require more cable than cable-stayed bridges.
 - **Aerodynamic stability & stiffness**: Suspension bridges require decks with higher flexural and torsional stiffness than cable-stayed bridges.

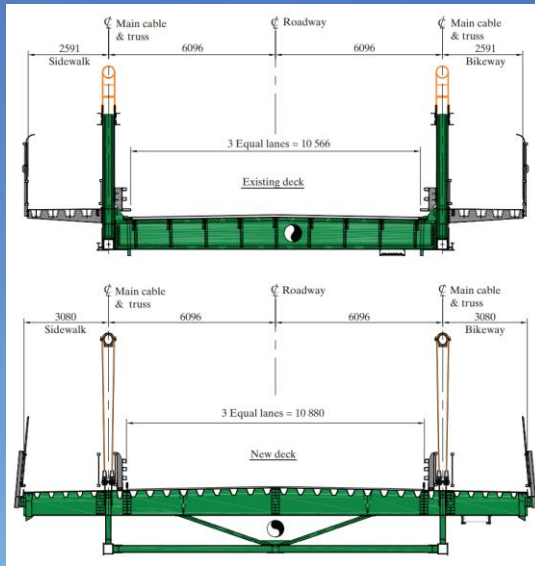


Cable-supported bridges – Cable-Stayed Bridges: **Conceptual Design**

Suspension cable anchorage construction (Akashi Kaikyo Bridge):



Cable-supported bridges – Cable-Stayed Bridges: **Conceptual Design**



Cable-supported bridges – Cable-Stayed Bridges: **Conceptual Design**

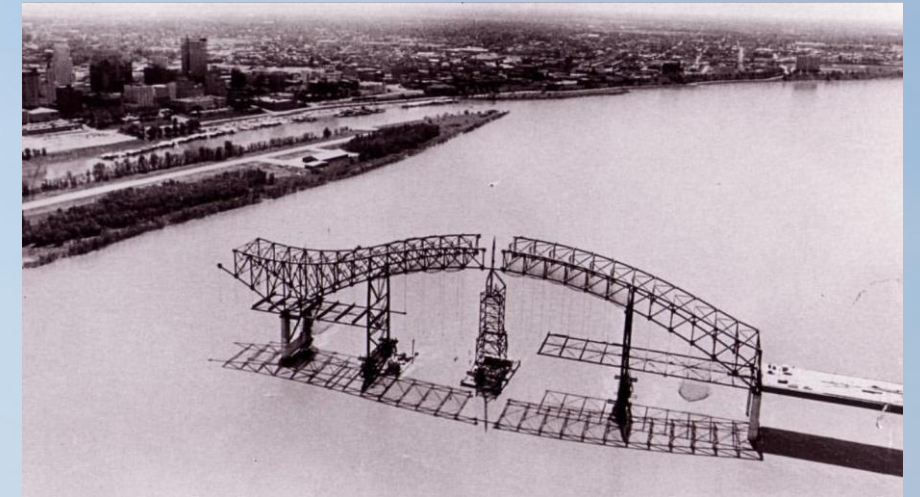
- Planning and bridge concept selection:
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 - For medium to long spans (200 ... 500 m) there are **several competing typologies**:
 - Cantilever truss / Arch truss bridges: High life-cycle costs, spans up to 550 m
 - **Concrete true arch bridges**: Require specific ground conditions to resist thrusts, spans up to 450 m
 - Steel/CFST true arch bridges: High life-cycle costs, spans up to 600 m
 - Tied-arch bridges: Perceived lack of redundancy, spans up to 550 m
 - Concrete girder bridges: spans up to 300 m
 - Steel girder bridges: spans up to 300 m



Hoover Dam Bypass Bridge, USA, 2010. TYLI / HDR

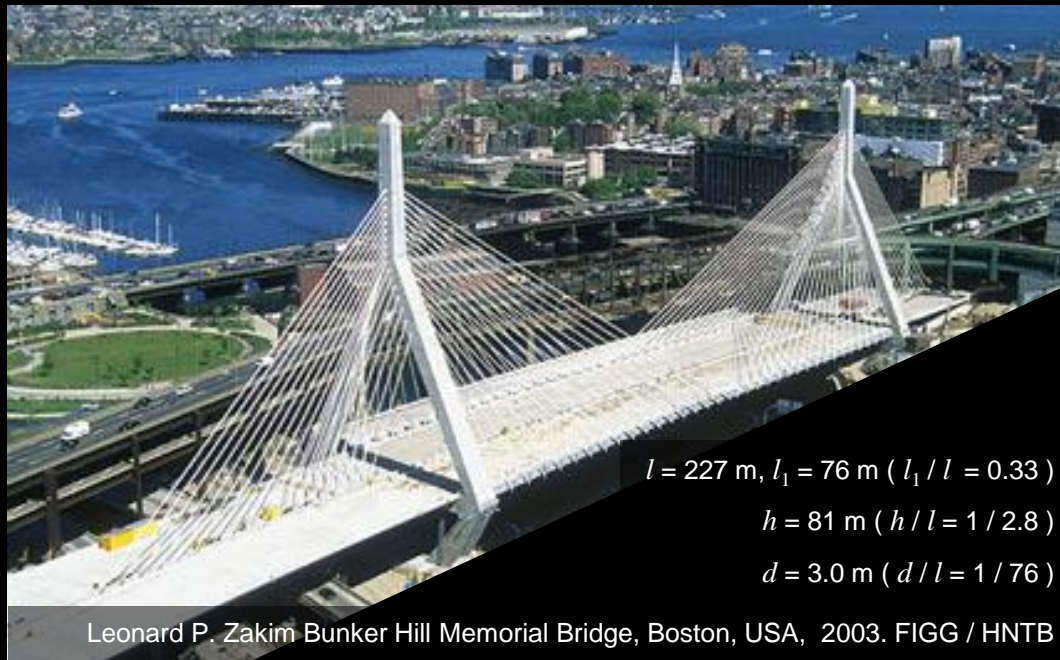


Cable-supported bridges – Cable-Stayed Bridges: **Conceptual Design**



Cable-supported bridges – Cable-Stayed Bridges: **Conceptual Design**

- Planning and bridge concept selection:
 - Based on **economic criteria alone** cable-stayed bridges could be the **preferred typology** for spans in the **200 ... 1100 m** range.
 - However, for **aesthetic reasons** (e.g. to avoid high visual impact) other typologies are often preferable despite not being the most economical solution.



Cable-supported bridges – Cable-Stayed Bridges: **Conceptual Design**

- Planning and bridge concept selection:
 - Based on economic criteria alone cable-stayed bridges could be the preferred typology for spans in the 200 ... 1100 m range.
 - However, for aesthetic reasons (e.g. to avoid high visual impact) other typologies are often preferable despite not being the most economical solution.
 - Also, **height restrictions** (e.g. due to proximity to an airport) may preclude the relatively tall towers required for a cable-stayed bridge. An **extradosed** bridge could be a viable alternative in this case (spans up to 270 m).



Rose Fitzgerald Kennedy Bridge, Ireland, 2020. Arup / Carlos Fernandez Casado SL.



Ibi Gawa Bridge, Japan, 2001. CTI Engineering Co. Ltd.

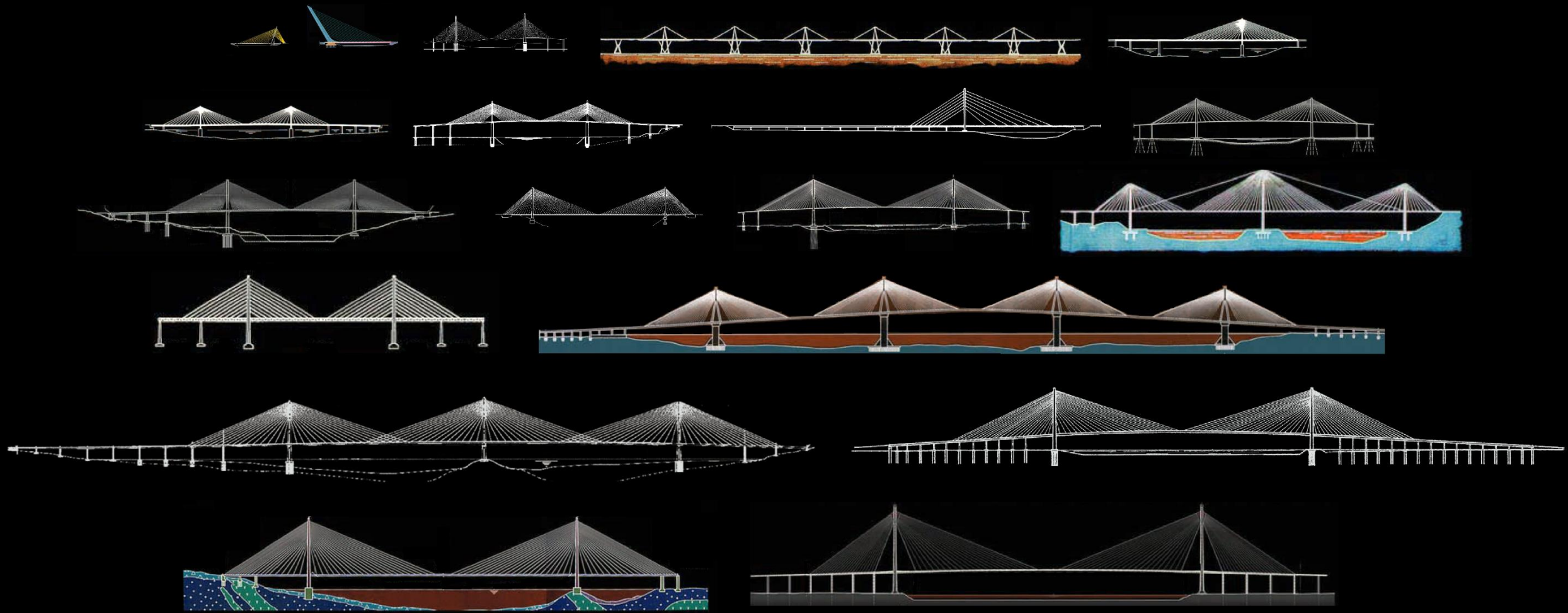
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 - Also, height restrictions (e.g. due to proximity to an airport) may preclude the relatively tall towers required for a cable-stayed bridge. An extradosed bridge could be a viable alternative in this case (spans up to 270 m).
 - Conversely, a cable-stayed bridge could be selected for spans **shorter than 200 m** when a signature bridge is desired.
 - **Increased cost** for towers and cables **must be accepted**
 - **Inherent complexities** of this typology are **still present** even for relatively short spans



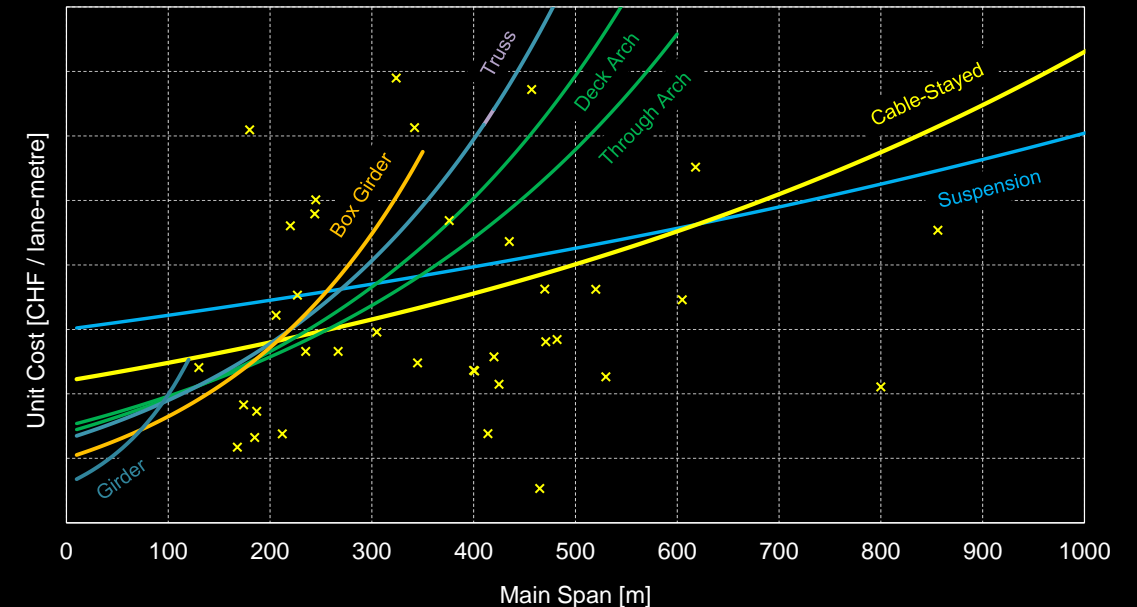
Esplanade Riel, Winnipeg, Canada, 2003. Buckland & Taylor Ltd.

Cable-supported bridges – Cable-Stayed Bridges: **Conceptual Design**



Cable-supported bridges – Cable-Stayed Bridges: **Conceptual Design**

- Planning and bridge concept selection:
 - **Unit costs** for cable-stayed bridges vary considerably:
 - Due to **wide range** of spans
 - Due to **special conditions** associated with mega-projects
 - Due to **aesthetics-related** choices
 - In order to achieve an economic design, we must understand the **economics** of cable-stayed bridge **construction**:
 - What constitutes the “**base case**” design?
 - What are the features requiring a **premium** over the “base case” and when/how these should be added?



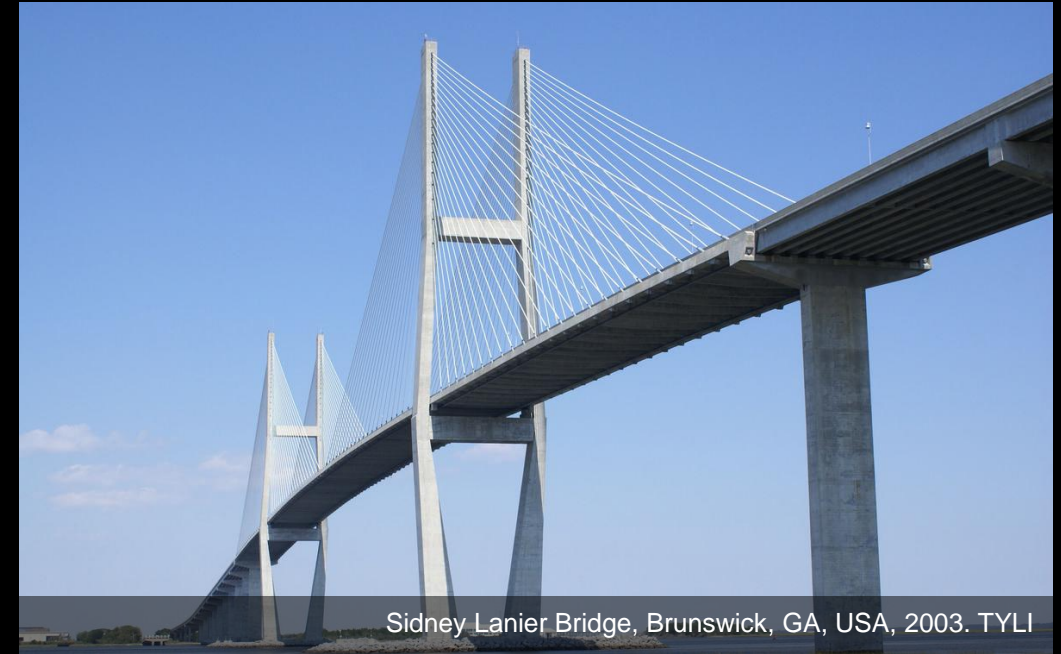
Seri Wawasan Bridge, Putrajaya, Malaysia, 2003. PJSI

Cable-supported bridges – Cable-Stayed Bridges: **Conceptual Design**

- Planning and bridge concept selection:
 - “**Base Case**” Cable-Stayed Bridge:
 - Minimalist solution: **nothing can be taken away**
 - Aesthetically pleasing if carefully executed
 - Basic features of design concept:
 - **Symmetry** about mid-span and centreline
 - **Closely spaced** stay cables
 - Two **vertical** towers, two anchor piers (three spans)
 - **Semi-fan** stay cable arrangement in vertical plane(s)



- | | |
|--|---|
| • Open cross-section:
edge girder & floor beam
(composite or concrete) | • Closed cross-section:
box girder
(concrete) |
| • Two cable planes | • One cable plane |
| • H-tower | • Single tower |



Sidney Lanier Bridge, Brunswick, GA, USA, 2003. TYLI



Puente Centenario (Panama Canal Second Crossing), Panama, 2004. TYLI / LAP

Cable-supported bridges – Cable-Stayed Bridges: **Conceptual Design**

- Planning and bridge concept selection:

Enhancements to the “base case” design resulting to a **cost premium** may be required due to:

→ **Wind** (aerodynamic) effects:

- Tower: “A” or Inverted “Y”
- Girder: Streamlined box cross-section

→ **Seismic** effects:

- Increased strength and/or ductility demands (more complicated detailing)
- Special devices: Lock-up-devices, energy dissipating dampers, tuned-mass dampers

→ **Hardening**:

- Important structures often require an Accident and Terrorist Vulnerability Assessment (ATVA)
- Protection of stay cables against fire, blast, cutting charges, etc.

→ **Aesthetic** requirements



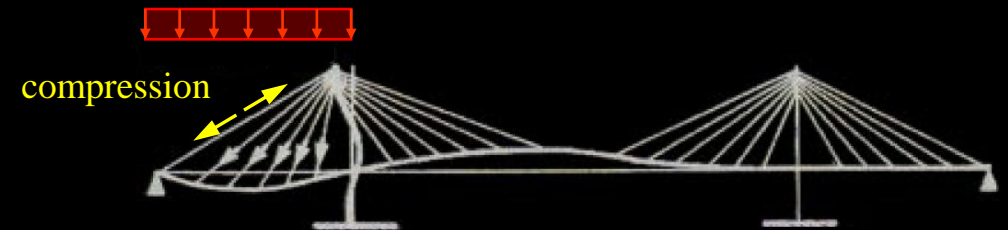
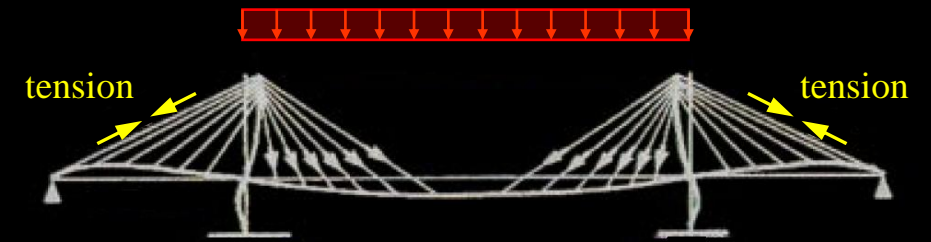
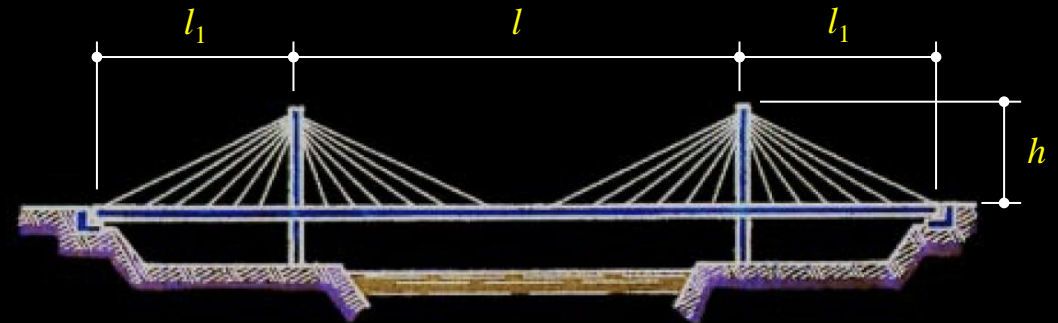
Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

- Basic proportions of cable-stayed bridges:

The geometry of cable-stayed bridges is determined by the following ratios:

→ Side spans (l_1) to main span (l) ratio:

- Backstays** govern the **stiffness** of the bridge and are subject to significant **stress reversals**
- l_1 / l ratio determines the **fatigue stress range** in the **backstays** and demands for **tie-down devices / counterweights** at anchor piers



Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

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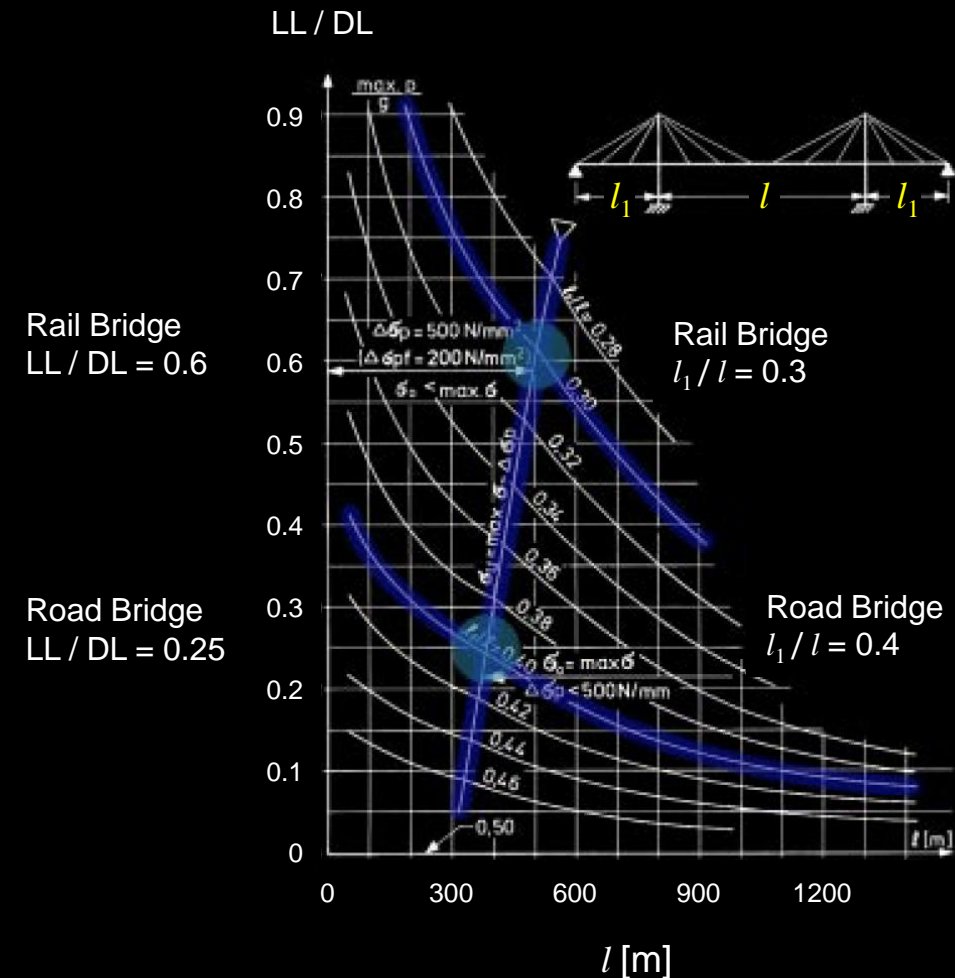
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- l_1 / l ratio determines the **fatigue stress range** in the **backstays** and demands for **tie-down devices / counterweights** at anchor piers
- Optimum l_1 / l ratio depends on LL / DL ratio:
 - Road bridges, $l_1 / l = 0.4 \dots 0.5$
 - Rail bridges, $l_1 / l = 0.3 \dots 0.4$

→ Tower height (h) to main span (l) ratio:

- Controlled by flattest stay: optimum angle ≈ 23 deg (inclination ca. 40%)
- Optimum h / l ratio $\approx 1/5$ (compare to 1/10 for suspension bridges)

Recommended side span / main span ratios [Svensson 2012]



Cable-supported bridges – Cable-Stayed Bridges: **Conceptual Design**

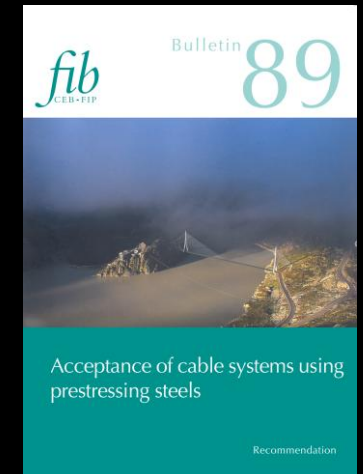
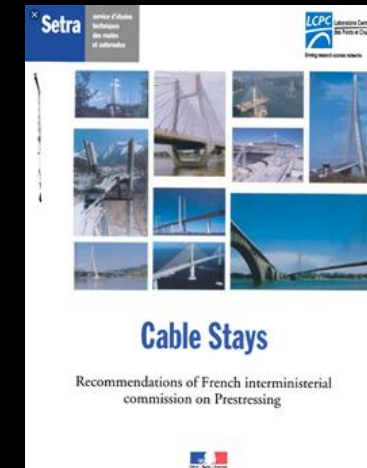
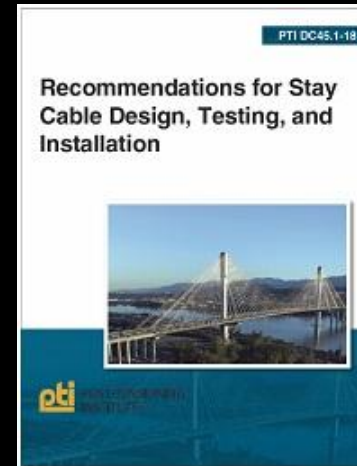
- Design Development:

- **Project Specific Design Criteria:**

Long-span, cable-supported bridges are typically **not fully covered** by the provisions of **standard bridge codes**. Topics that may require development of project-specific criteria (→ service criteria agreement) may include:

- Load combinations
- Serviceability requirements, e.g. deflection limits
- Wind loading / Aerodynamic vibrations
- **Stay cable systems acceptance criteria**
- Progressive collapse requirements (e.g. accidental cable loss)

- **Guideline documents** for stay cable design, testing and installation have been developed to **supplement** the standard bridge codes



Cable-supported bridges

Cable-stayed bridges – **Structural Response**

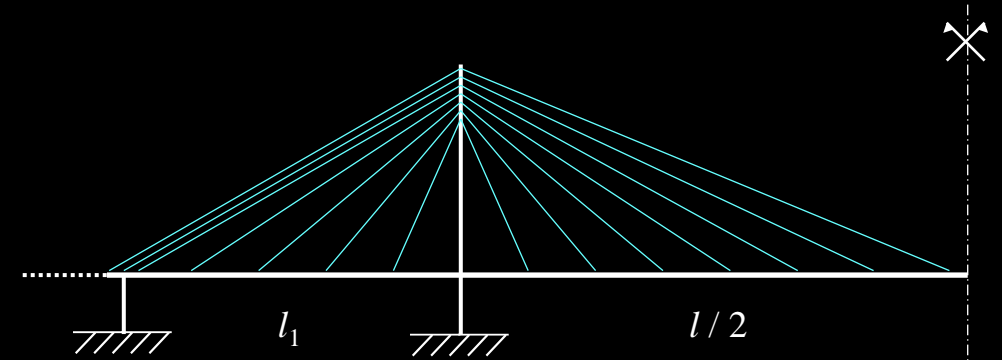
Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

- Basic load-carrying mechanism of a cable-stayed bridge:

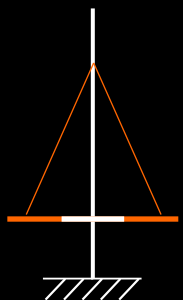
→ Response to **Dead Load**:

Stay cables:

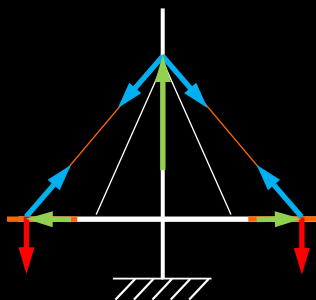
- Each stay cable can be assumed to support a tributary length of the girder
- Backstays are the exception: they are used to resist the unbalanced load in the main span



Stage i-1

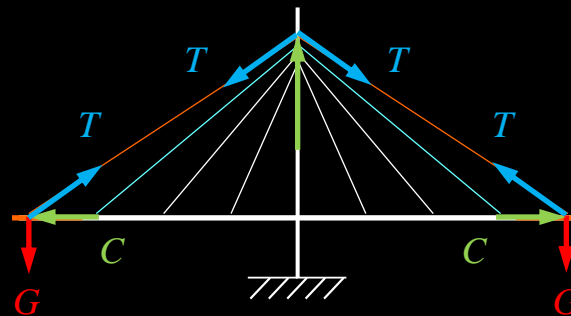


Stage i



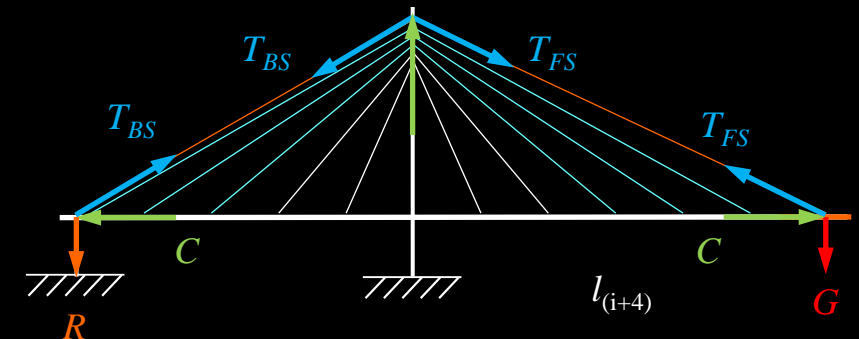
...

Stage i + 2



...

Stage i + 4



$$R = G \cdot \frac{l_{(i+4)}}{l_1}$$

Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

- Basic load-carrying mechanism of a cable-stayed bridge:

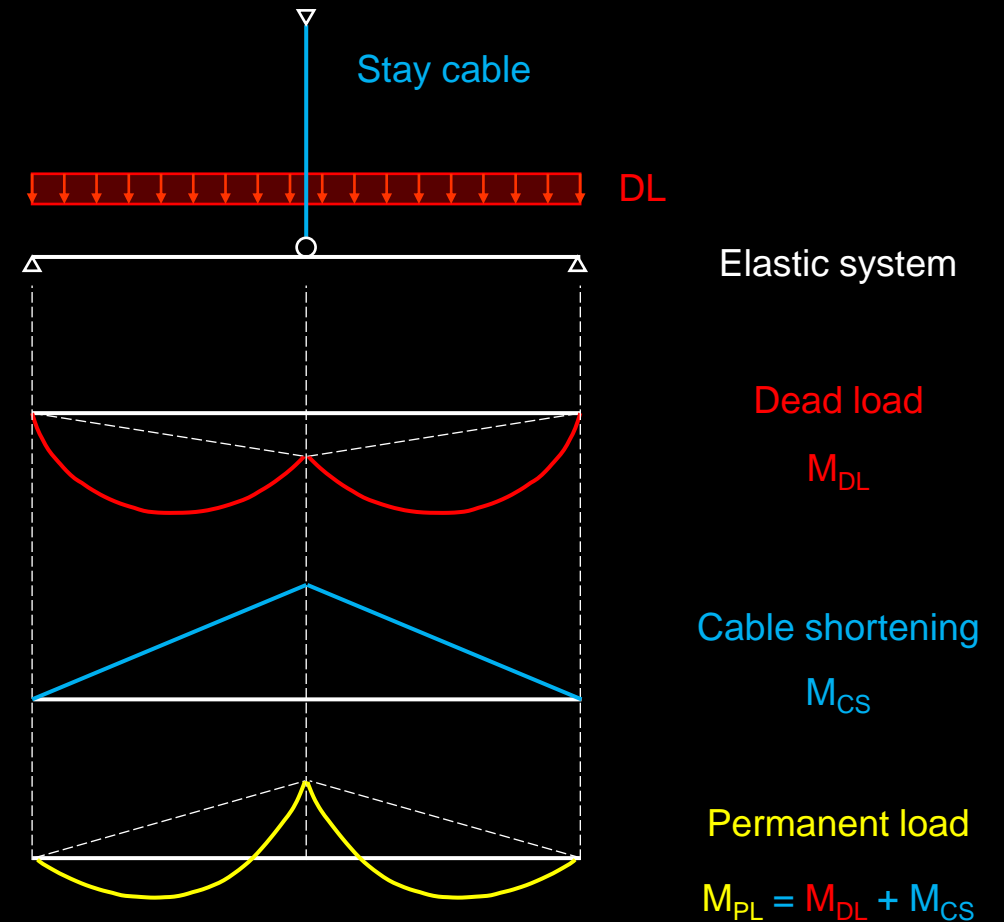
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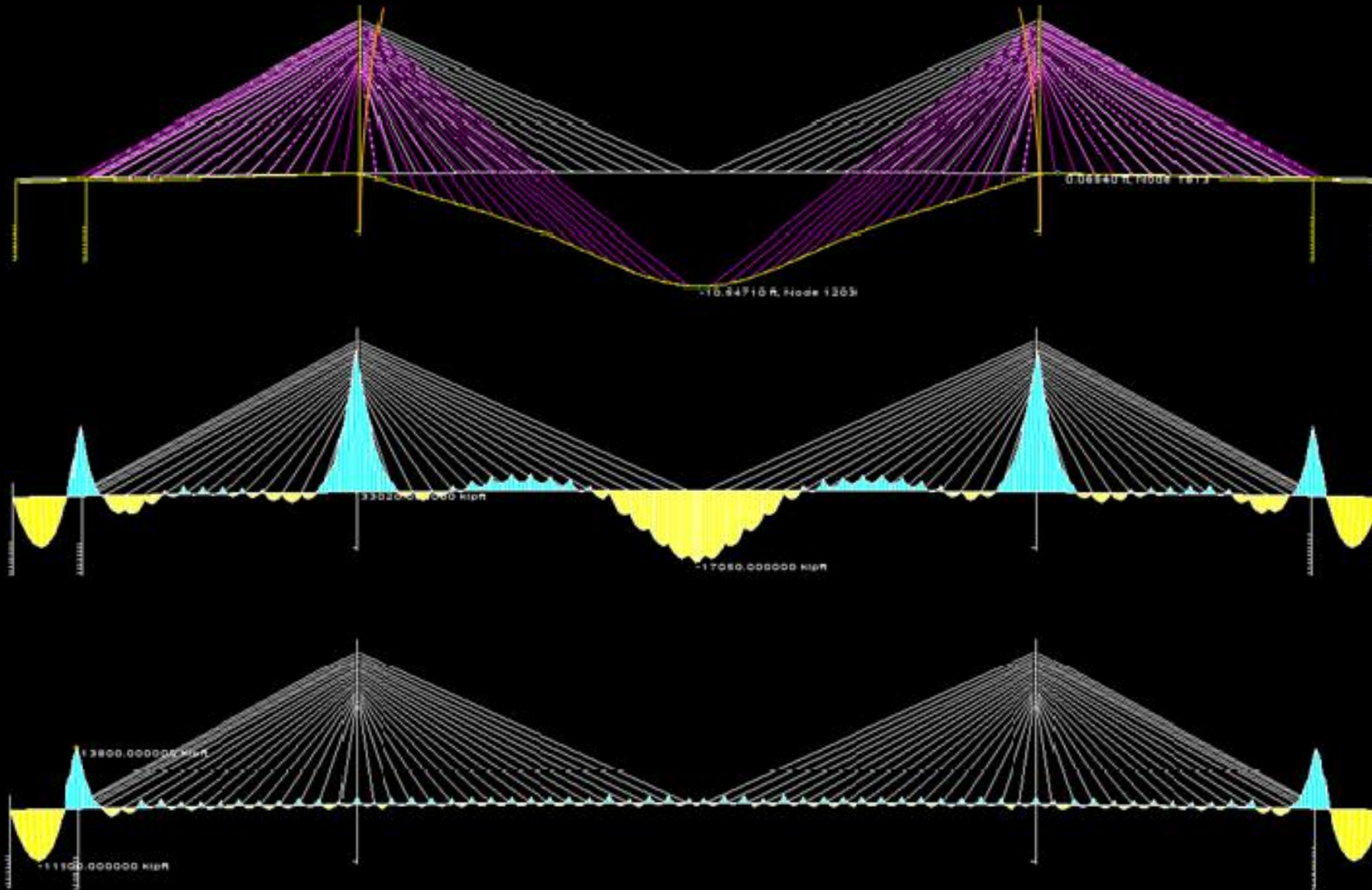
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Girder:

- DL application on the elastic system results in significant deflections and corresponding moments
- Appropriate cable shortenings are required to restore the girder to the target profile and moment diagram



Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**



Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

- Basic load-carrying mechanism of a cable-stayed bridge:

→ Response to **Live Load** - Characteristic Influence Lines:

Stay cables:

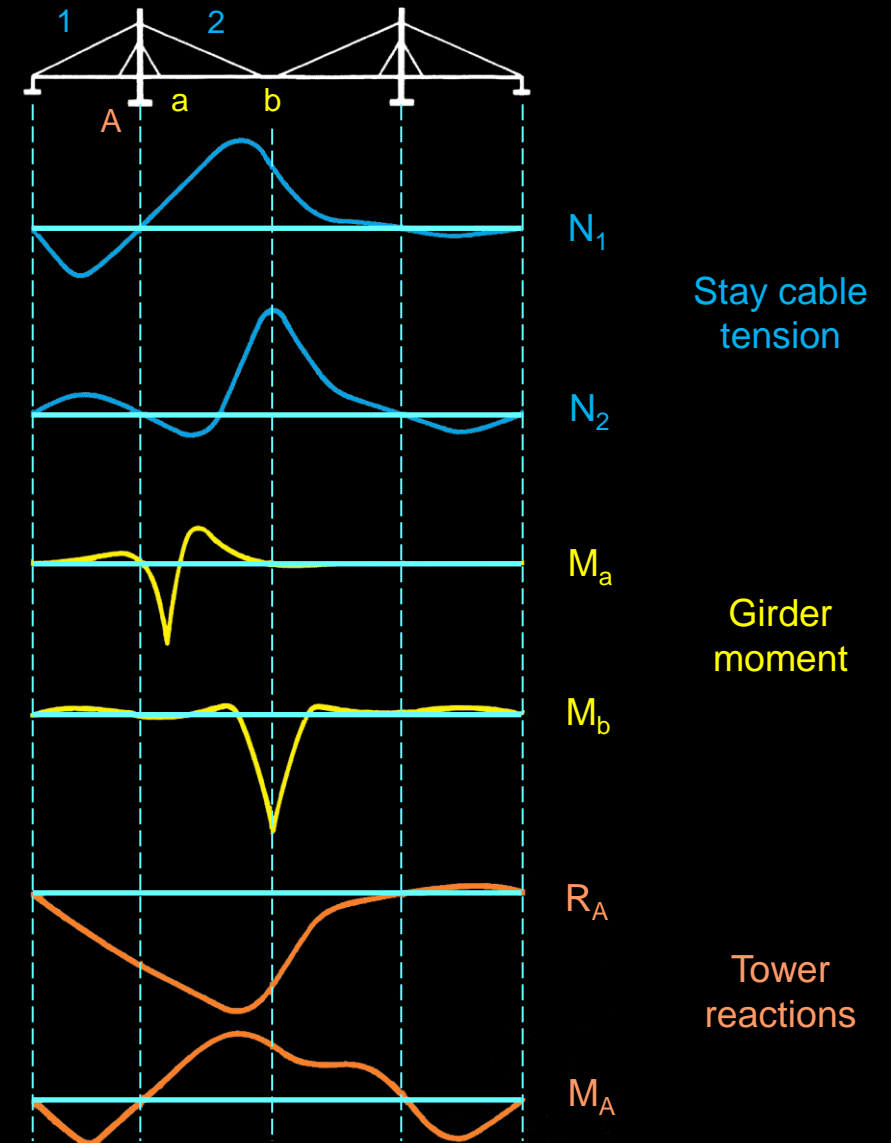
- The backstay function is fundamental to the efficiency of the bridge
- Backstays have very “broad” influence line: design controlled by fatigue in railway bridges (fatigue loads extending over large portion of span)

Girder:

- Behaviour similar to beam on elastic foundation
- Function of girder stiffness, cable stiffness and cable spacing

Towers / Anchor Piers:

- Provided that the tower is anchored through backstays to an anchor pier, the tower resists mainly vertical reactions
- In the absence of an anchor pier, the influence of the tower stiffness to the girder response is much more pronounced (see also multi-span cable-stayed bridges)

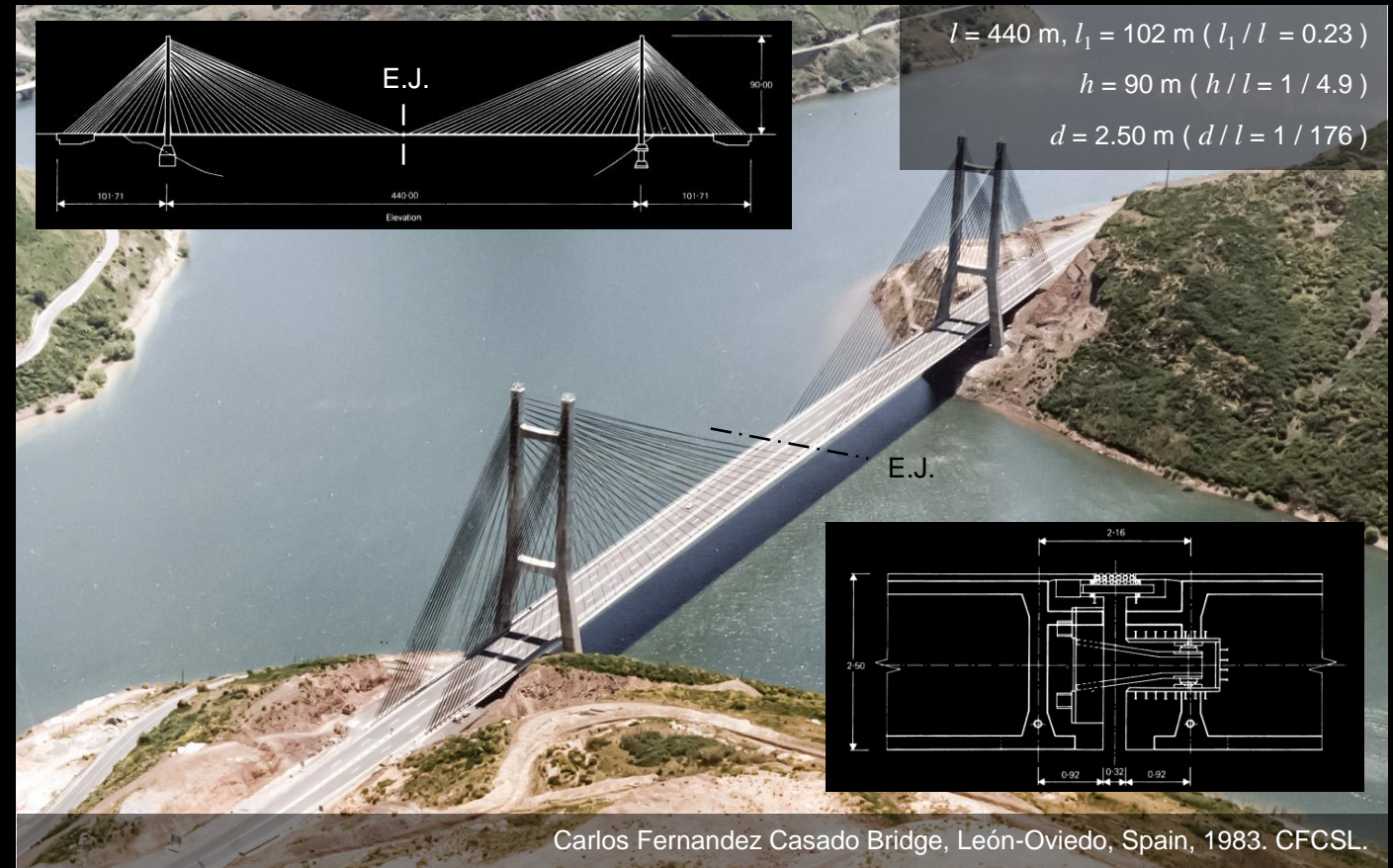


Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

- Particularities of cable-stayed bridges:

→ **Support and articulation**

- Girder must be continuous through towers (highest axial compression), but can be articulated at mid-span (not recommended)
- Girder is commonly articulated at anchor piers, but may also be made continuous with the approach span girder
- The connection between the girder and towers / anchor piers in the vertical, longitudinal and transverse directions can be tailored to best fit the governing loading and site conditions:
 - ✓ The concepts presented in the Support and Articulation section are generally applicable

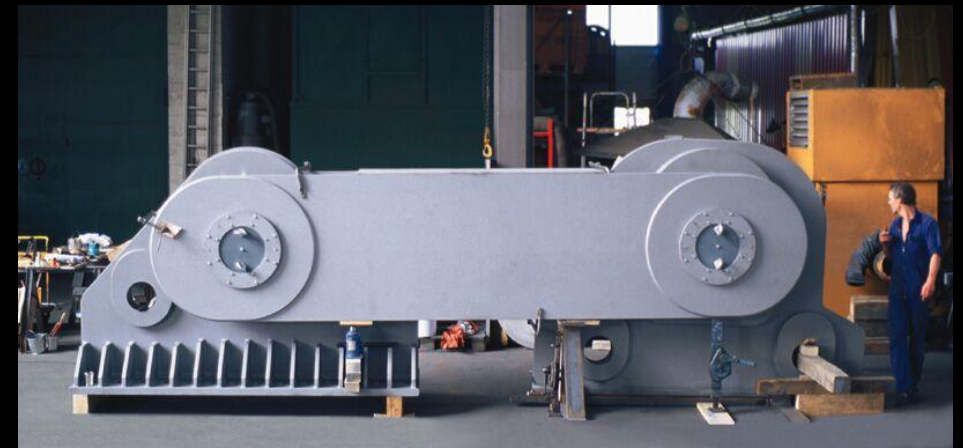


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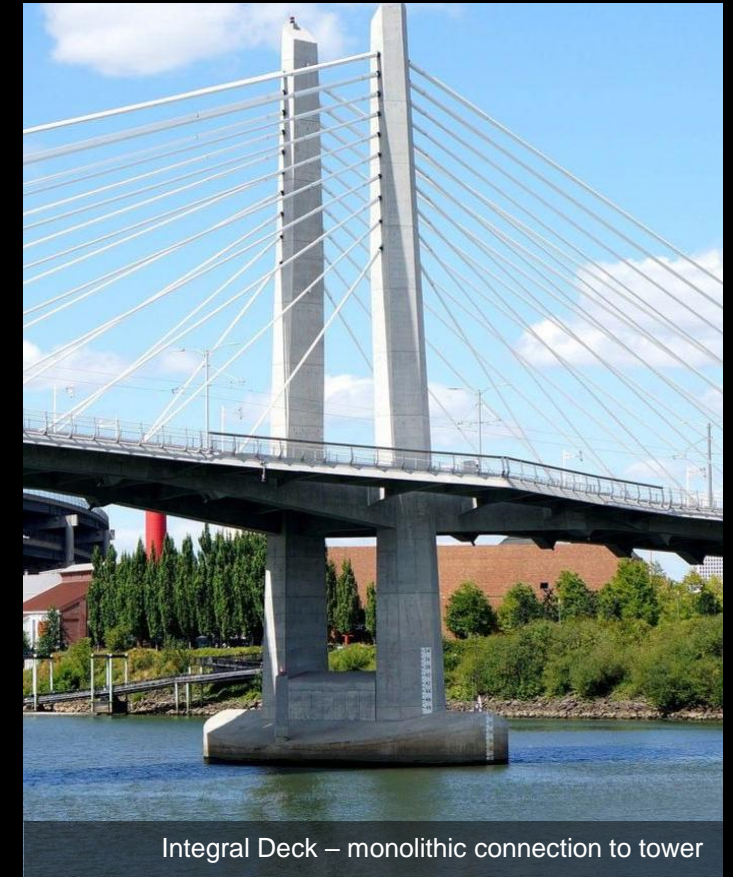
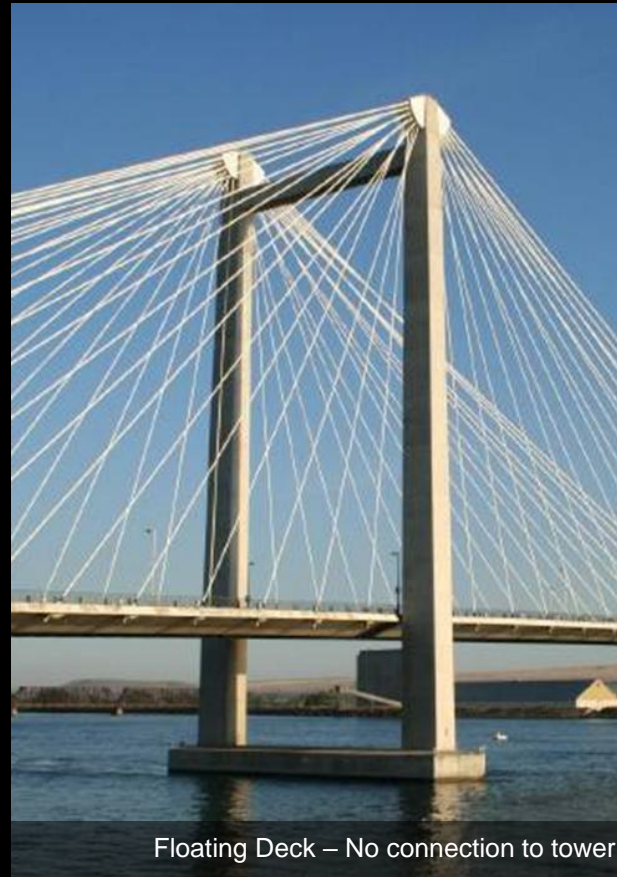


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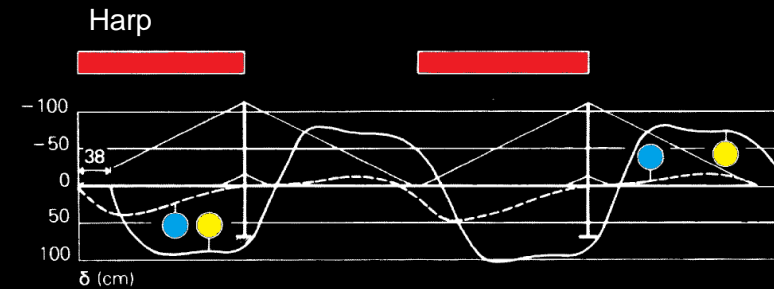
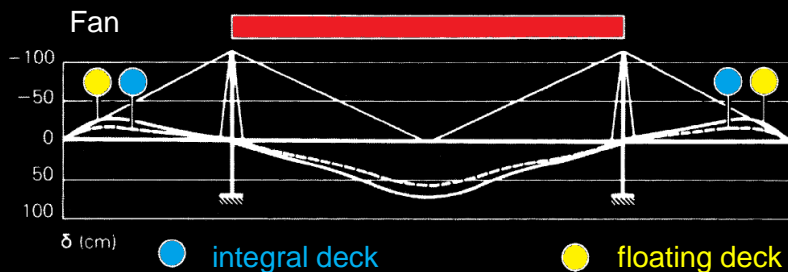
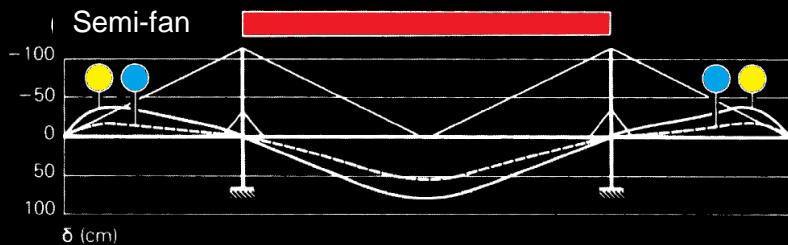
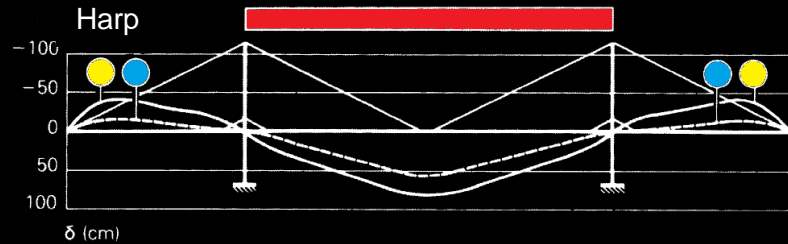


Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

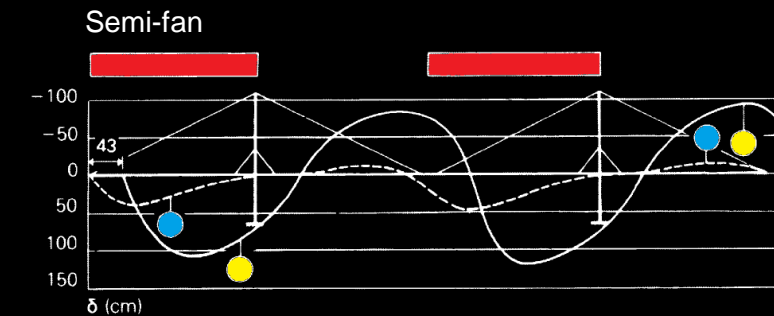
- Particularities of cable-stayed bridges:

→ **Support and articulation** – influence of girder/tower connection [*modified after Walther et al. 1999*]:

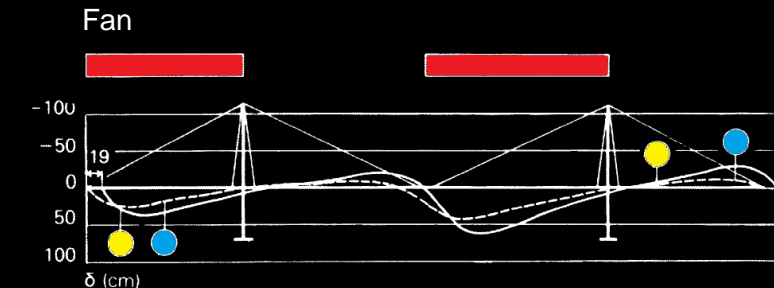
Deck deformations under LL for the two extreme cases (integral/floating):



Asymmetric LL causes longitudinal deck displacement



Vertical deflections can increase 3x when deck is released



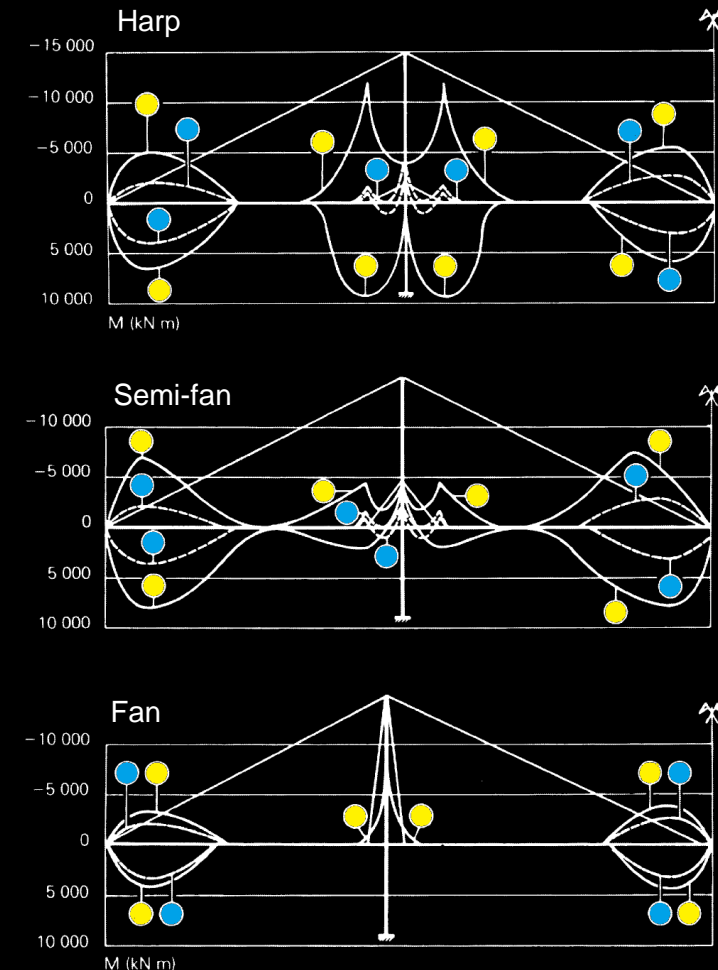
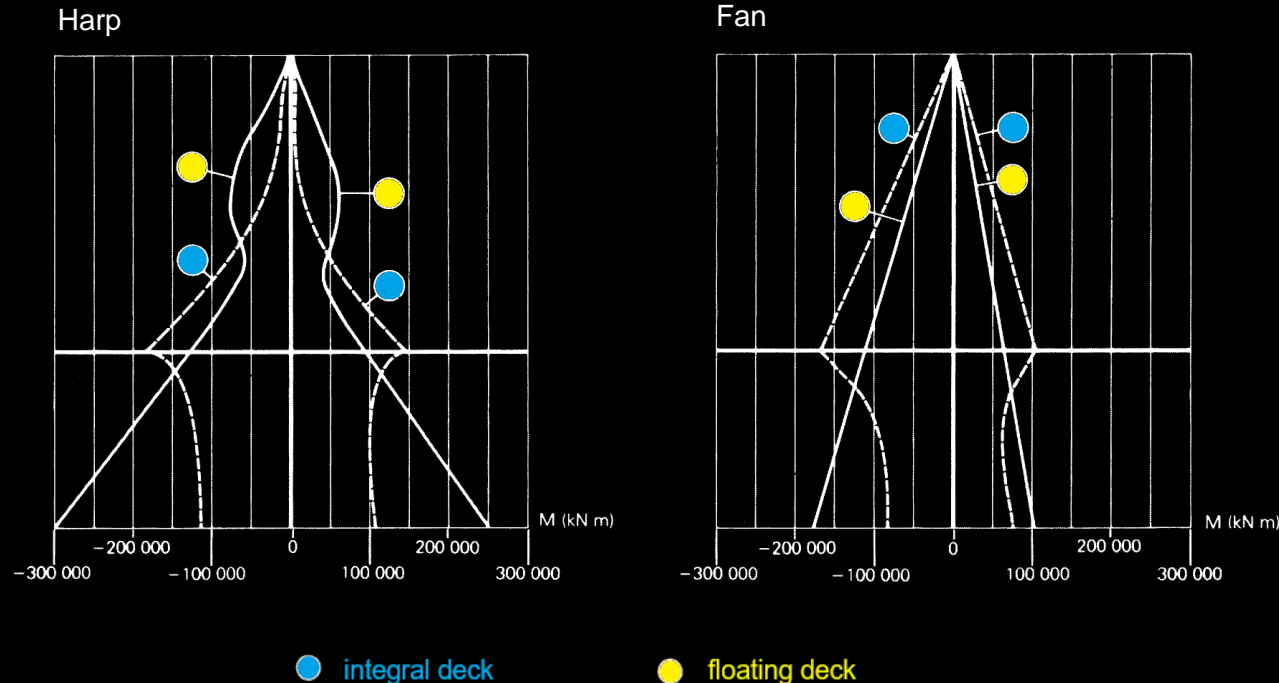
LL effects are less sensitive to deck articulation for fan pattern

Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

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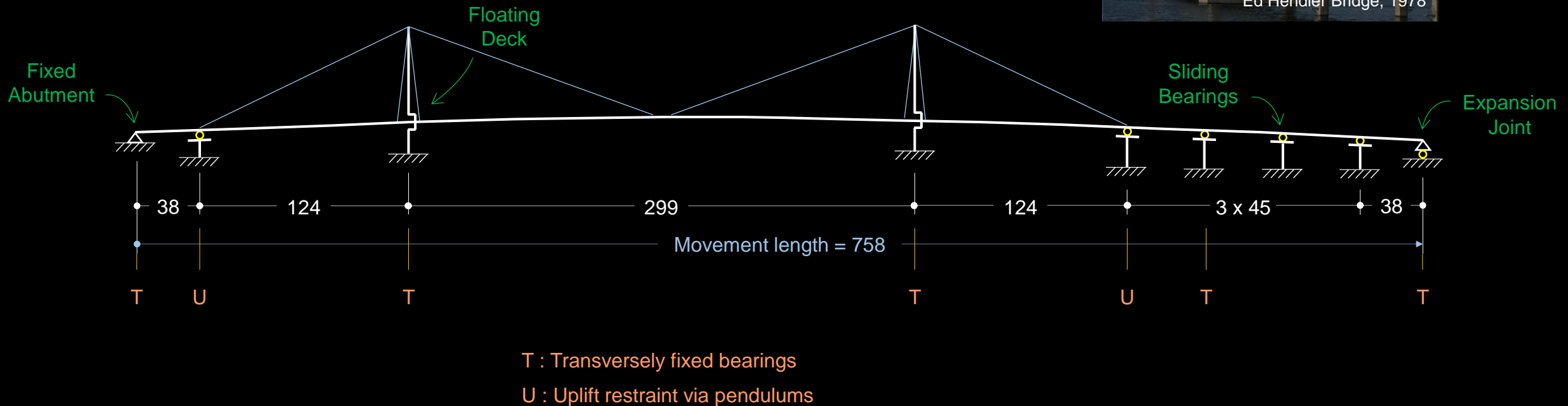
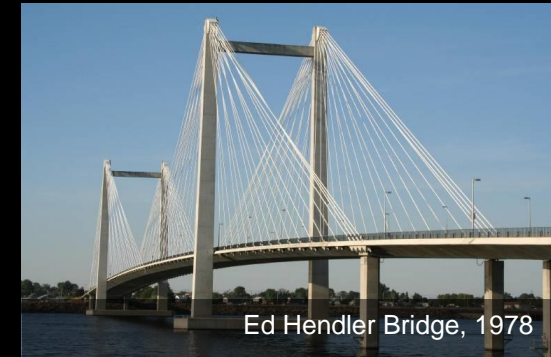
Tower & Deck moment envelopes under LL for the two extreme cases (integral/floating):



LL effects are less sensitive to deck articulation for fan pattern

Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

- Particularities of cable-stayed bridges:
 - **Support and articulation** – Example



Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

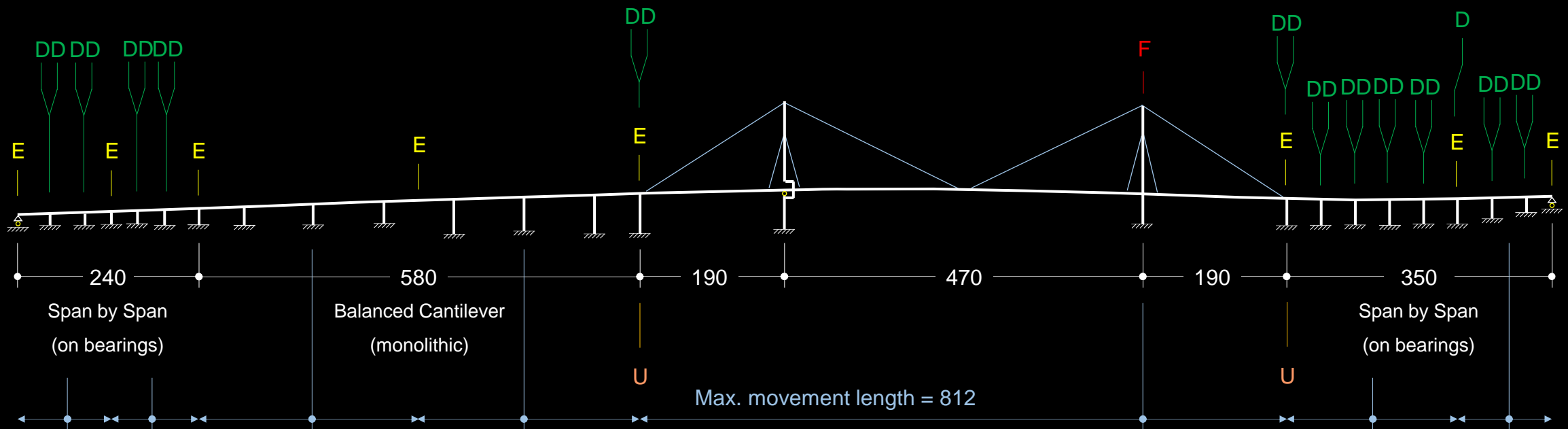
- Particularities of cable-stayed bridges:
→ **Support and articulation** – Example

E : Expansion joint

F : Longitudinal fixed bearings

U : Uplift restraint via sliding tie-downs

D : Viscous dampers (longitudinal)



Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

- Particularities of cable-stayed bridges:

→ **Tower stability**

- Towers are typically slender and subject to high axial compressive forces → **2nd order effects important**
- Towers are often **most vulnerable** during the **construction** phase: **boundary** and **loading conditions** are less favourable than in the final state
- Flexural stiffness and strength are a **function of the axial load**

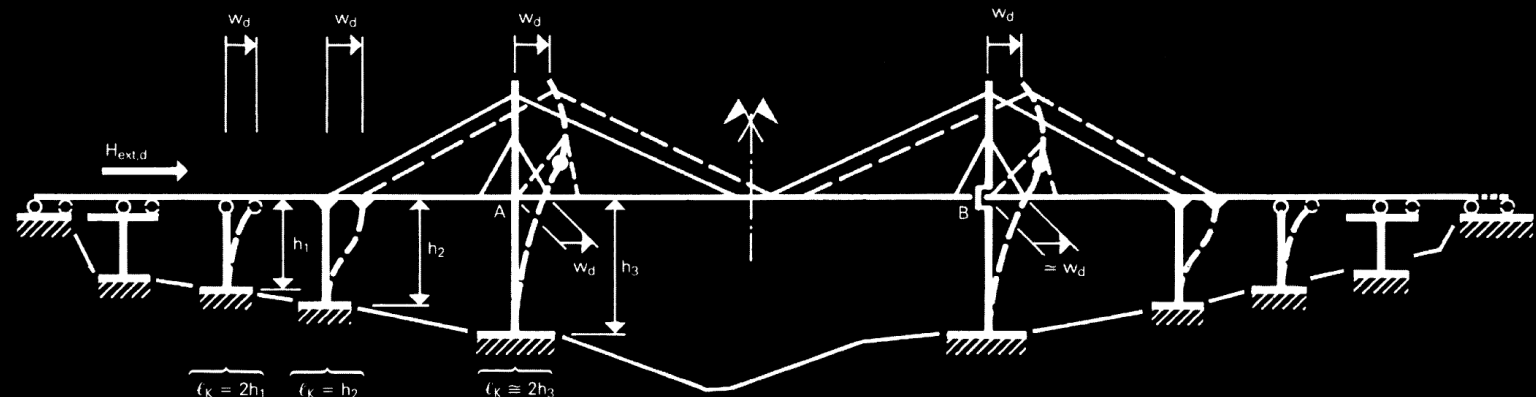
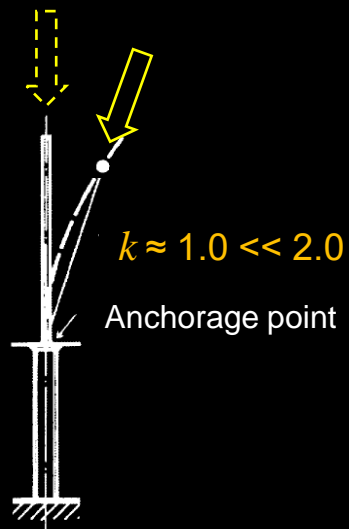
Buckling load depends on EI and kL :

$$P_{cr} = \pi^2 \frac{EI}{(kL)^2}$$

EI varies based on the level of cracking

$$k_{\min} = 0.8 \quad \left(\frac{k_{\max}}{k_{\min}} \right)^2 = 6.25$$

$$k_{\max} = 2.0$$



Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

- Particularities of cable-stayed bridges:

→ **Tower stability** - Example

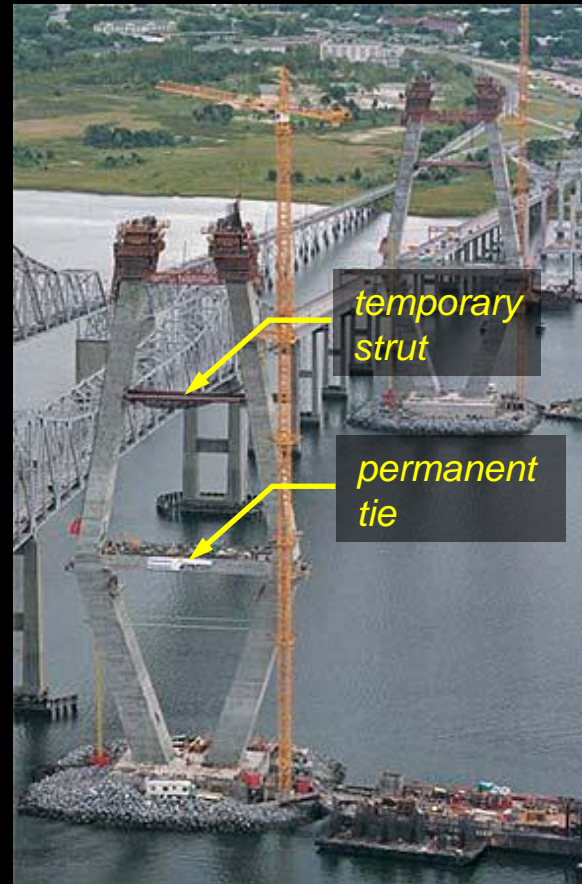


Arthur Ravenel Jr. (Cooper River) Bridge, SC, USA, 2005. Parsons Brinkerhoff Quade & Douglas

Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

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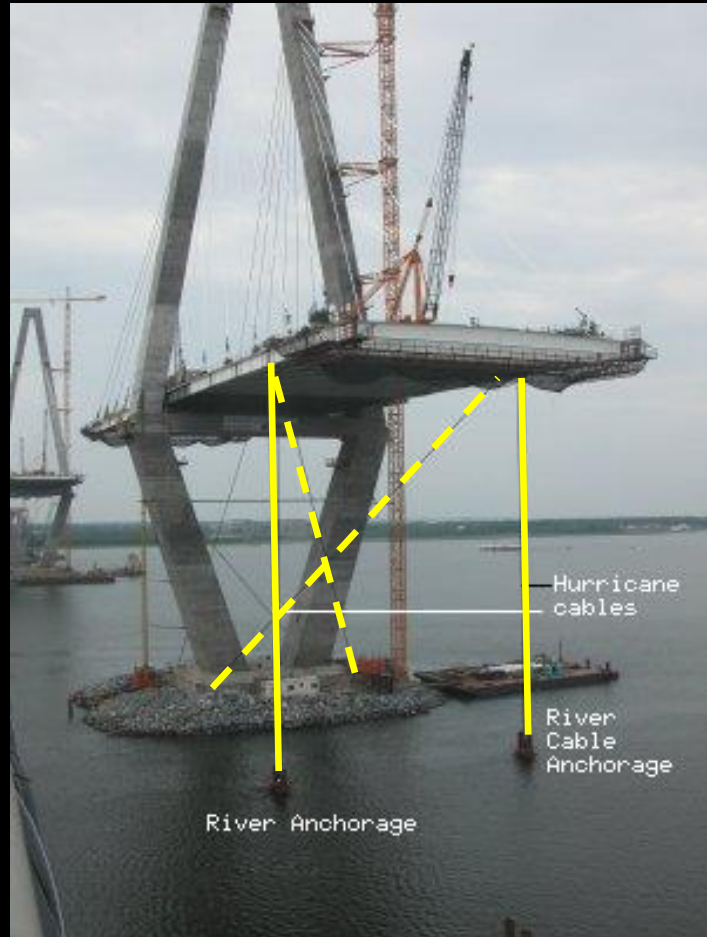
→ **Tower stability** - Example



Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

- Particularities of cable-stayed bridges:

→ **Tower stability** - Example



Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

- Particularities of cable-stayed bridges:
 - **Tower stability** - Example



Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

- Particularities of cable-stayed bridges:
 - Redundancy requirements: **Accidental cable loss**
 - Modern cable-stayed bridges are designed with **closely-spaced** stay cables so that accidental loss of a cable will not result in **progressive collapse**
 - Furthermore, stay cables are considered **replaceable** components and therefore cable exchange must be possible **during service**
 - **Planned cable exchange** is performed strand by strand and therefore imposes **static loading** to the structure
 - **Accidental cable loss**, depending on the cause, can be relatively sudden (i.e. relative to the eigenfrequencies of the bridge) and must therefore be treated as **dynamic loading**



Seohae Grand Bridge, South Korea, 2000. TYLI

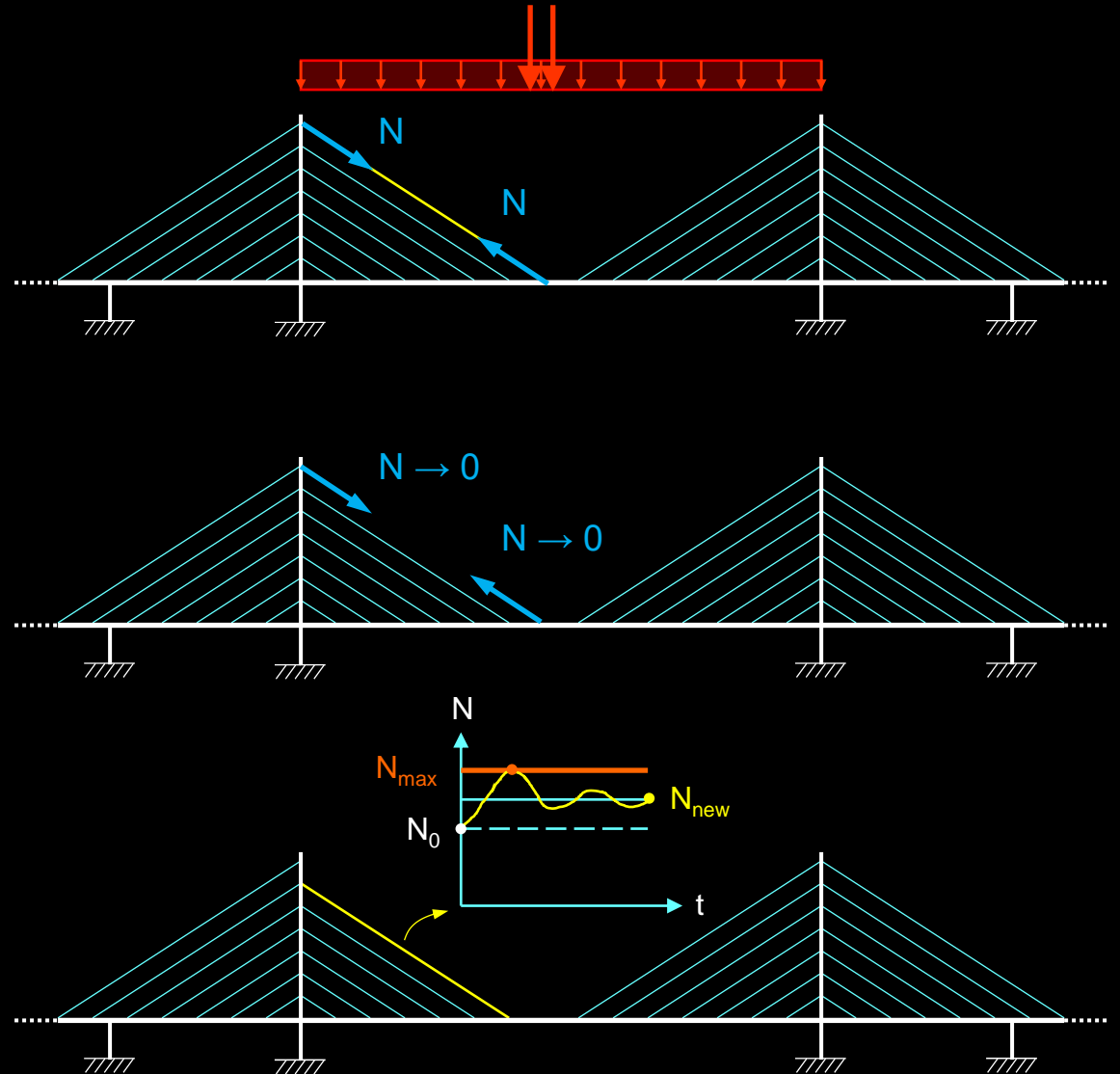
Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

- Particularities of cable-stayed bridges:

→ Redundancy requirements: **Accidental cable loss**

Time-history analysis approach:

1. Apply LL that maximises the axial force of the stay cable in question to the intact structure and obtain the total axial force in the cable for the considered load combination
2. Remove stay cable in question from model and replace with corresponding reactions to tower and girder (initial conditions)
3. Run time-history analysis by removing cable reactions (reduce cable reaction to zero over a **short time step**)
4. Record response of structure over time, capture peak and final force effects and check that structure remains stable
5. Repeat steps 1 to 4 for all cables



Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

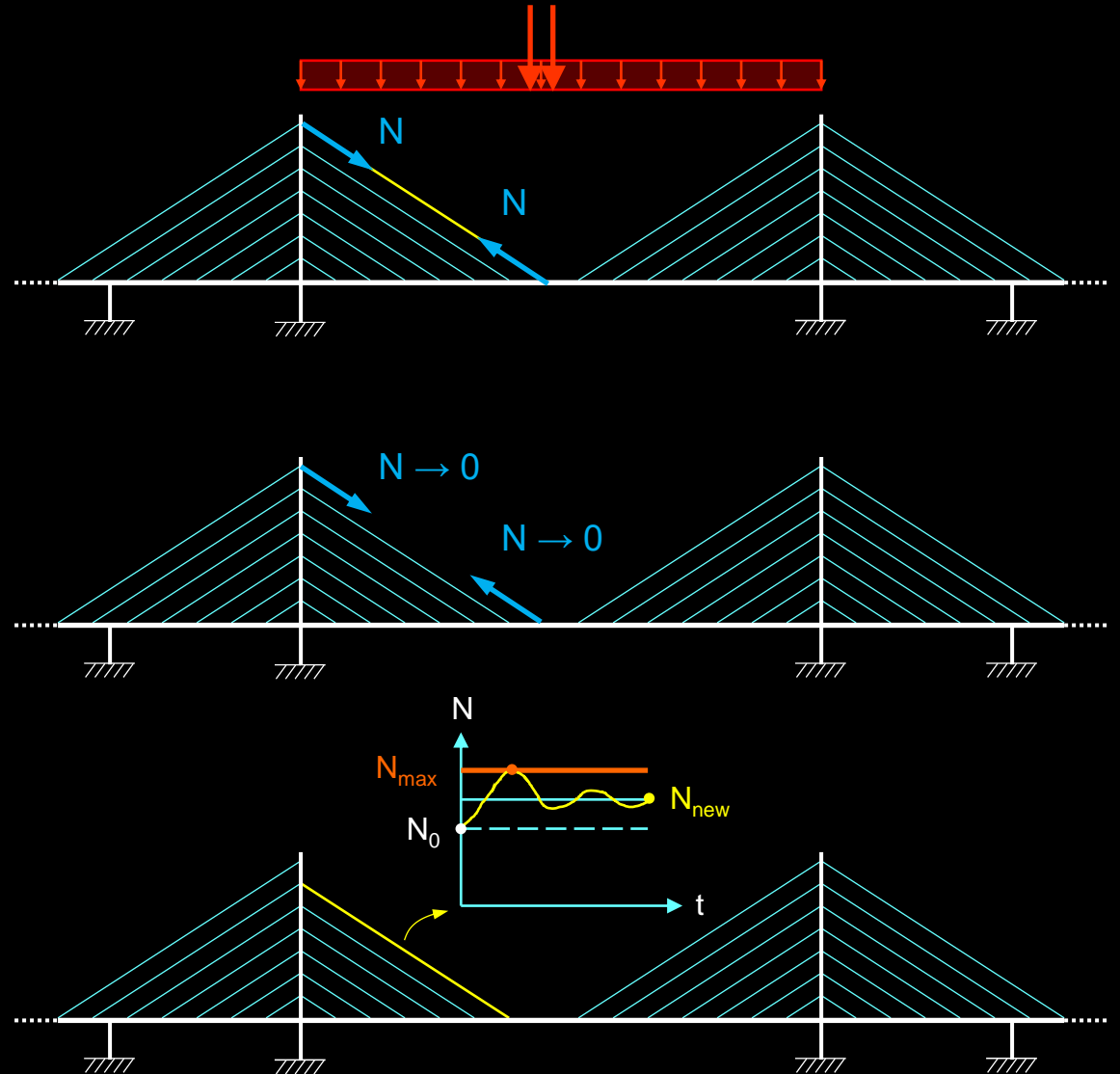
- Particularities of cable-stayed bridges:

→ Redundancy requirements: **Accidental cable loss**

Time-history analysis approach:

- Most **precise** approach
- Can consider geometric and material nonlinearities
- Selected material **damping** coefficients and **time-step** of cable loss can affect response significantly
- **Labour/data intensive**
- Can be avoided if a dynamic amplification factor of 2.0 is used in conjunction with a static approach (conservative)
- Can be used **selectively** to prove out dynamic amplification factors **less than 2.0**

$$N_{\max} = N_0 + (N_{\text{new}} - N_0) \cdot DAF \rightarrow DAF = \frac{N_{\max} - N_0}{N_{\text{new}} - N_0}$$



Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

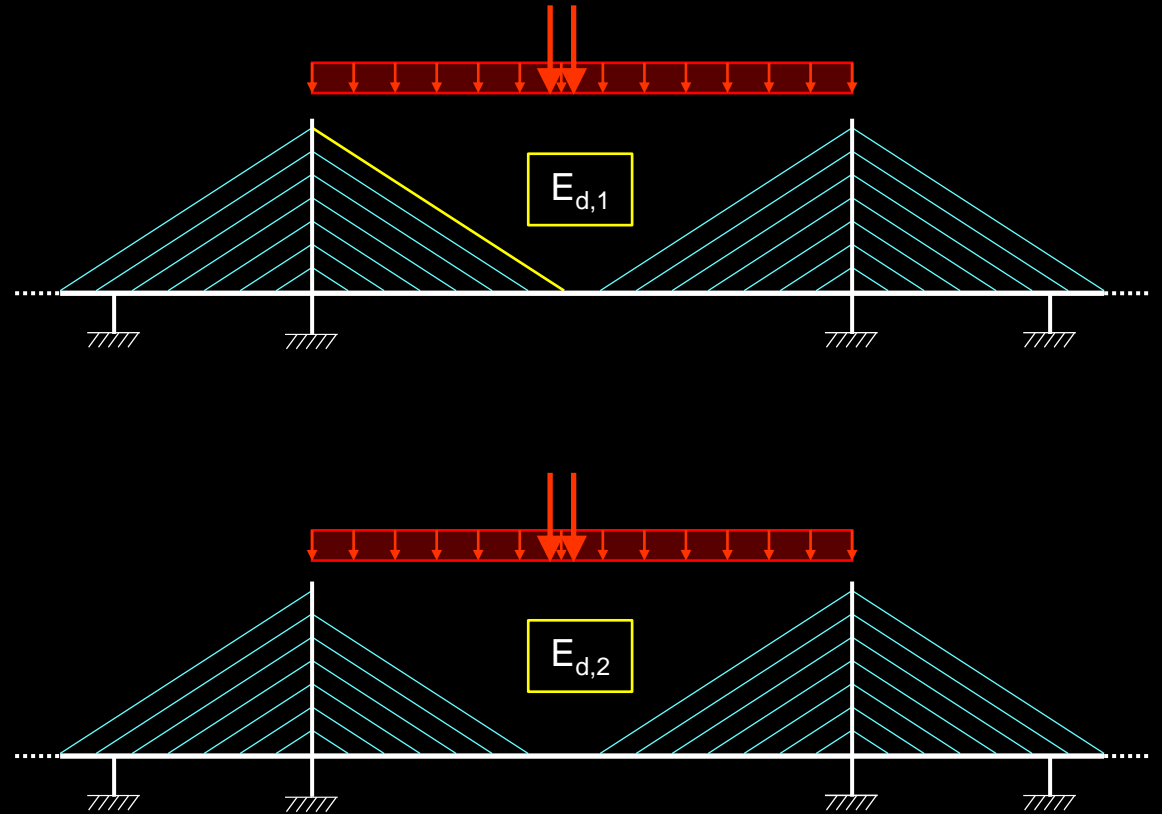
- Particularities of cable-stayed bridges:

→ Redundancy requirements: **Accidental cable loss**

Eurocode (static) approach:

1. Apply LL that maximises the axial force of the stay cable in question to the intact structure and calculate design effect: $E_{d,1}$
2. Remove stay cable in question from model and calculate design effect under the same loading: $E_{d,2}$
3. Calculate the difference between the design effects: $\Delta E = E_{d,2} - E_{d,1}$
4. Total design effect = $E_d = E_{d,1} + 2 \Delta E$

Dynamic Amplification Factor



Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

- Particularities of cable-stayed bridges:

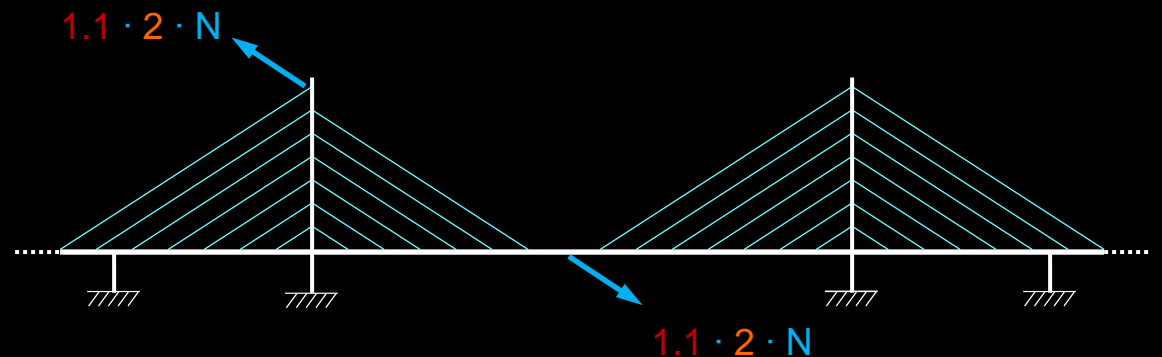
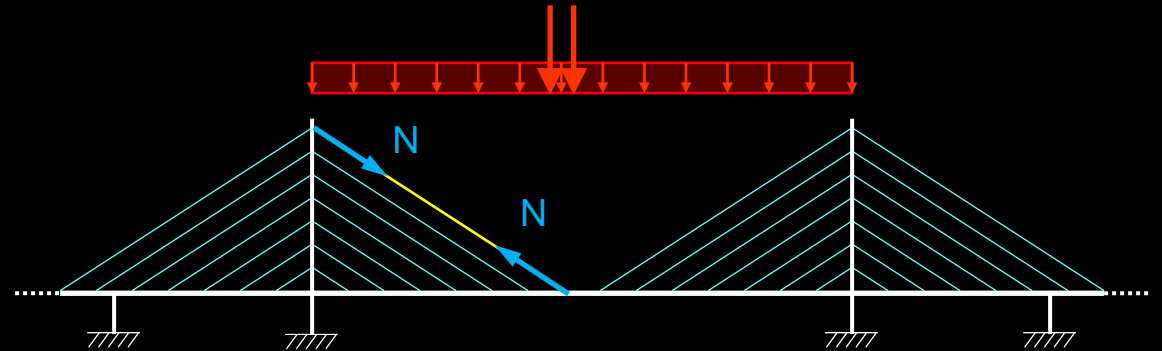
→ Redundancy requirements: **Accidental cable loss**

PTI (static) approach:

1. Apply LL that maximises the axial force of the stay cable in question to the intact structure and obtain the total axial force (N) in the cable for the following load combination:

$$1.1 \text{ DC} + 1.35 \text{ DW} + 0.75 (\text{LL} + \text{IM})$$

2. Remove stay cable in question from model and replace with corresponding reactions (N) to tower and girder, applied in the opposite directions and multiplied with a load factor of **1.1** and a dynamic amplification factor of **2.0** (unless a lower factor can be determined from a non-linear dynamic analysis, but **not < 1.5**)
3. Superimpose effects of Steps 1 & 2 to obtain total load effects



Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

- Particularities of cable-stayed bridges:

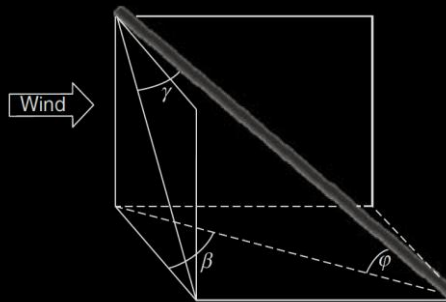
→ **Stay cable vibration** (see also lecture on Common Aspects)

Cable vibrations can be generated by:

- **Wind**: dry/**wet galloping** (most cases), buffeting or vortex-shedding (rarely)
- Loading of bridge girder or towers

Rain-wind-induced vibrations:

- Creation of water rivulets along a significant length of the cable → apparent modification in cable shape → galloping
- Wind tunnel testing show that cables are particularly vulnerable when:
 - ✓ Smooth
 - ✓ Lightly damped
 - ✓ Declining in direction of wind
 - ✓ Modal frequencies = 0.5 ... 3.3 Hz
 - ✓ Wind speed = 5 ... 18 m/s
 - ✓ Relative yaw angle (γ) = 0 ... 45 deg



Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

- Particularities of cable-stayed bridges:

→ **Stay cable vibration** (see also lecture on Common Aspects)

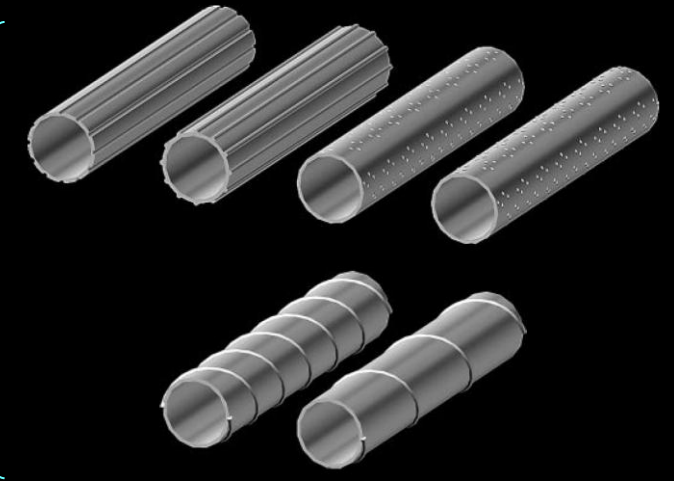
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Rain-wind-induced vibrations:

- Creation of water rivulets along a significant length of the cable → apparent modification in cable shape → galloping
- Wind tunnel testing show that cables are particularly vulnerable when:
 - ✓ Smooth → **provide surface modifications to HDPE pipe**
 - ✓ Lightly damped → **provide mechanical damping**
 - ✓ Declining in direction of wind
 - ✓ Modal frequencies = 0.5 ... 3.3 Hz
 - ✓ Wind speed = 5 ... 18 m/s
 - ✓ Relative yaw angle (γ) = 0 ... 45 deg

Types of surface modifications to HDPE pipe



External dampers near deck anchorages

Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

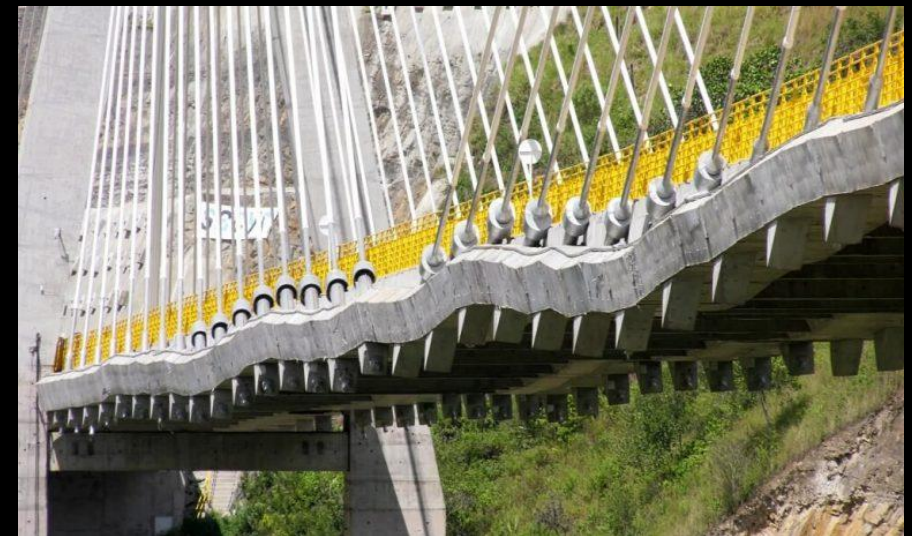
- Particularities of cable-stayed bridges:

→ **Time-dependent effects**

- The principles discussed for cantilever-constructed bridges with respect to:
 - ✓ Creep + shrinkage
 - ✓ Camber
 - ✓ Erection equipment weight
 - ✓ Prestressing
 - ✓ Change in structural system

are also applicable to cable-stayed bridges

- Note that the contribution of **tower creep** to the total **girder deflection** is **significant**.
- Due to the relative flexibility of the girder-tower system during erection, it is easier to adjust the profile by **adjusting the cable lengths** compared to conventional cantilever-constructed bridges.
- However, **errors are cumulative and grow quickly**, therefore **accurate monitoring and record keeping** during erection are paramount to ensure the correct final geometry



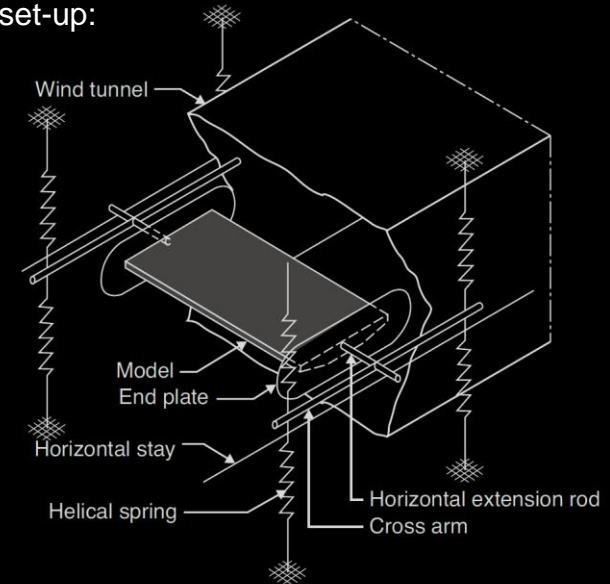
Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

- Particularities of cable-stayed bridges:

→ **Wind loading & aerodynamics**

- Code provisions apply to bridges with **negligible dynamic response**, i.e. road and rail bridges of spans up to 40 m (see Conceptual Design)
- For cable-stayed bridges, input from **wind specialists** is required:
 - Definition of **wind characteristics**:
 - Wind speed vs. Return period
 - Wind vs. Directionality
 - Turbulence (terrain roughness)
 - **Wind tunnel** testing
 - Virtual testing (CFD) - preliminary
 - **Sectional** testing
 - **Aeroelastic** testing

Sectional test set-up:



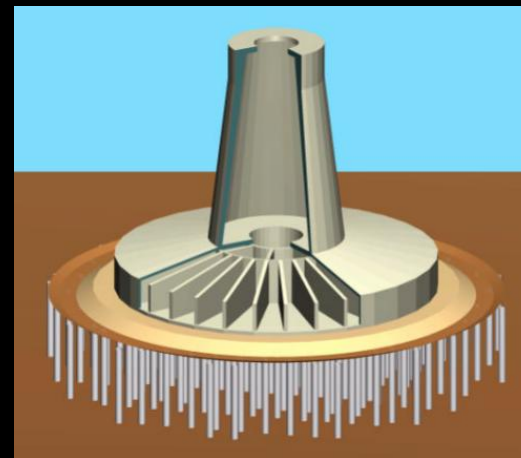
Cable-supported bridges – Cable-Stayed Bridges: **Structural Response**

- Particularities of cable-stayed bridges:

→ **Seismic design**

Depending on the **site seismicity**, the seismic design of cable-stayed bridges often extends beyond the standard code provisions:

- Input ground motions are developed based on **site-specific hazard analyses** for **multi-level events**; identification of faults running through bridge alignment
- Response is determined through non-linear, time-history analyses
- For long-span bridges, **spatial effects** (asynchronous seismic excitation) may need to be considered
- May involve **complex detailing** such as dampers, isolation bearings, fuses, special ductile elements



Cable-supported bridges

Cable-stayed bridges – Construction

Cable-supported bridges – Cable-Stayed Bridges: **Construction**

- Constructibility Aspects:

- **Early collaboration** between **designer** and **contractor** is essential to ensure an economic design and successful execution

- Erection method must be developed **during the design process** to ensure compatibility between design and erection and viability of the former

- Guiding principles:

- **Simplicity**
- **Repetition / Modularity**

- Common constructible girder types:

- **Precast concrete segmental**
- Cast-in-place concrete segmental
- Composite



Ed Hendler Bridge, Pasco/Kennewick, WA, USA, 1978. Arvid Grant & Associates / Leonhardt & Andrä



- ✓ **Precasting → Repetition**
- ✓ **Simplicity in connections between segments**
- **Economical if same section can be used for approaches: Cost of forms and erection equipment is amortised over greater length**
- **Simple lifting concept; heavy equipment required**

Cable-supported bridges – Cable-Stayed Bridges: **Construction**

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Sidney Lanier Bridge, Brunswick, GA, USA, 2003. TYLI



- ✓ **Repetitive & modular construction**
 - **Suitable for simple open cross sections**
 - **Alternative to precasting for shorter production runs (incl. approaches)**
 - Form travellers are complex and expensive (cannot be amortised over the approaches); schedule may require four travellers
 - Traveller imposes significant demands on girder (closely-spaced stays required); traveller may need to be temporarily supported by stays (complex details / load transfer)

Cable-supported bridges – Cable-Stayed Bridges: **Construction**

- Constructibility Aspects:

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- Erection method must be developed **during the design process** to ensure compatibility between design and erection and viability of the former

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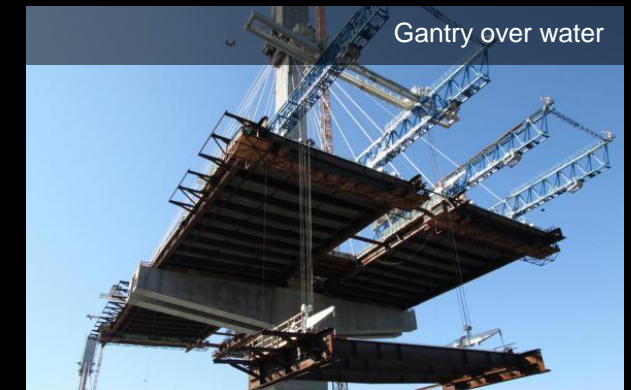
- **Simplicity**
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- Common constructible girder types:

- Precast concrete segmental
- Cast-in-place concrete segmental
- **Composite**



- ✓ **Repetitive & modular construction**
- **Suitable for simple open cross sections**
- ✓ **Simple pre-fabrication of plate girders and precast deck panels**
- ✓ **No need for formwork (infill strips over girder flanges)**
- **Cross-section shape not aerodynamic → wind fairings typically needed**



Cable-supported bridges – Cable-Stayed Bridges: **Construction**

- Erection:

→ Cable-stayed bridges are typically **most vulnerable** during erection

→ **Geometry Control:**

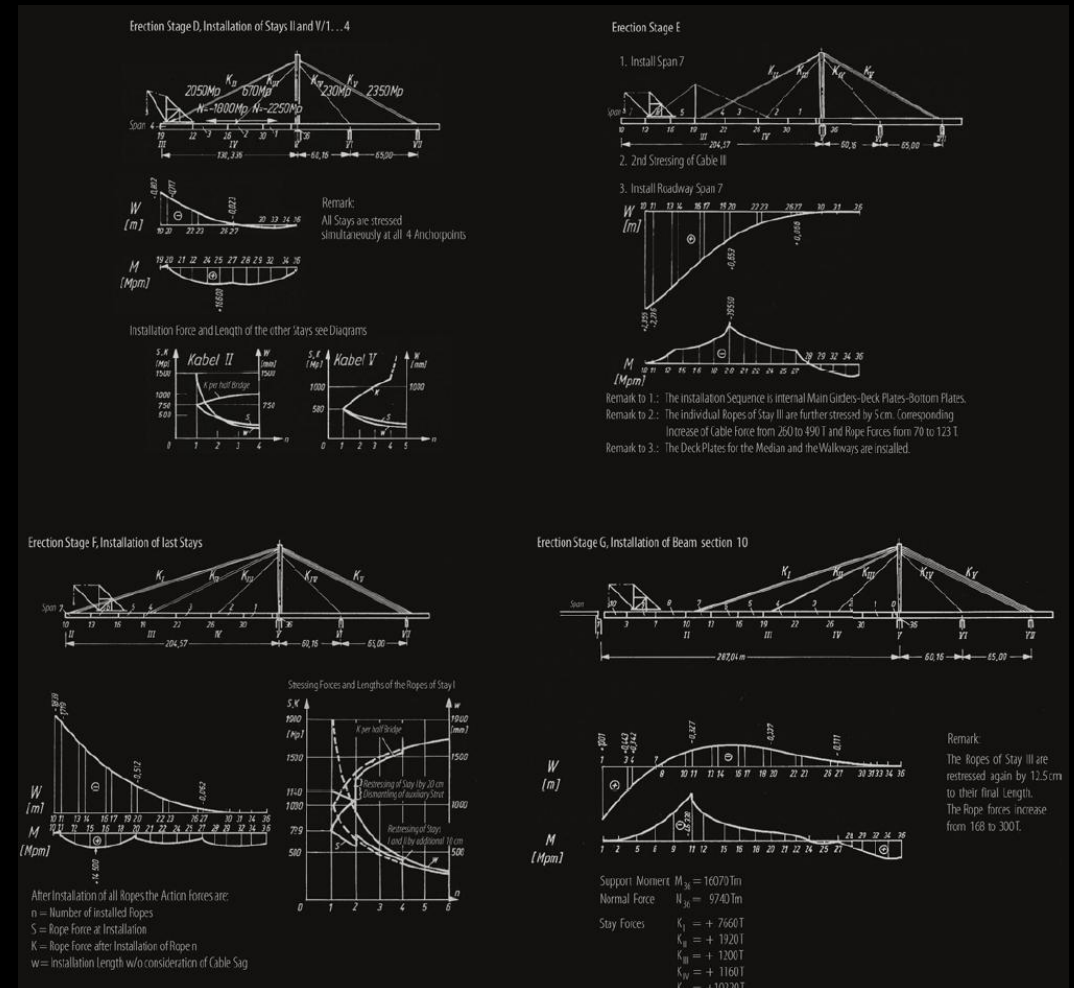
Assembly of information and methodology, used to control positions and dimensions of structural elements during erection (x, y, z, t)

- Goal: achieve **target geometry** and **stress state** at a reference stage (typically @ 10'000 days)
- Final stress state is dependent upon final geometry and key erection stages (“locked-in” stresses, closures) → **must track and control**

Key aspects:

- Modelling** of erection sequence
- Survey **monitoring** during erection
- Assessing** and **controlling** during erection (perform adjustments as/if needed)

Sample Erection Manual:



Cable-supported bridges – Cable-Stayed Bridges: **Construction**

- Erection:

- Stay cable installation:

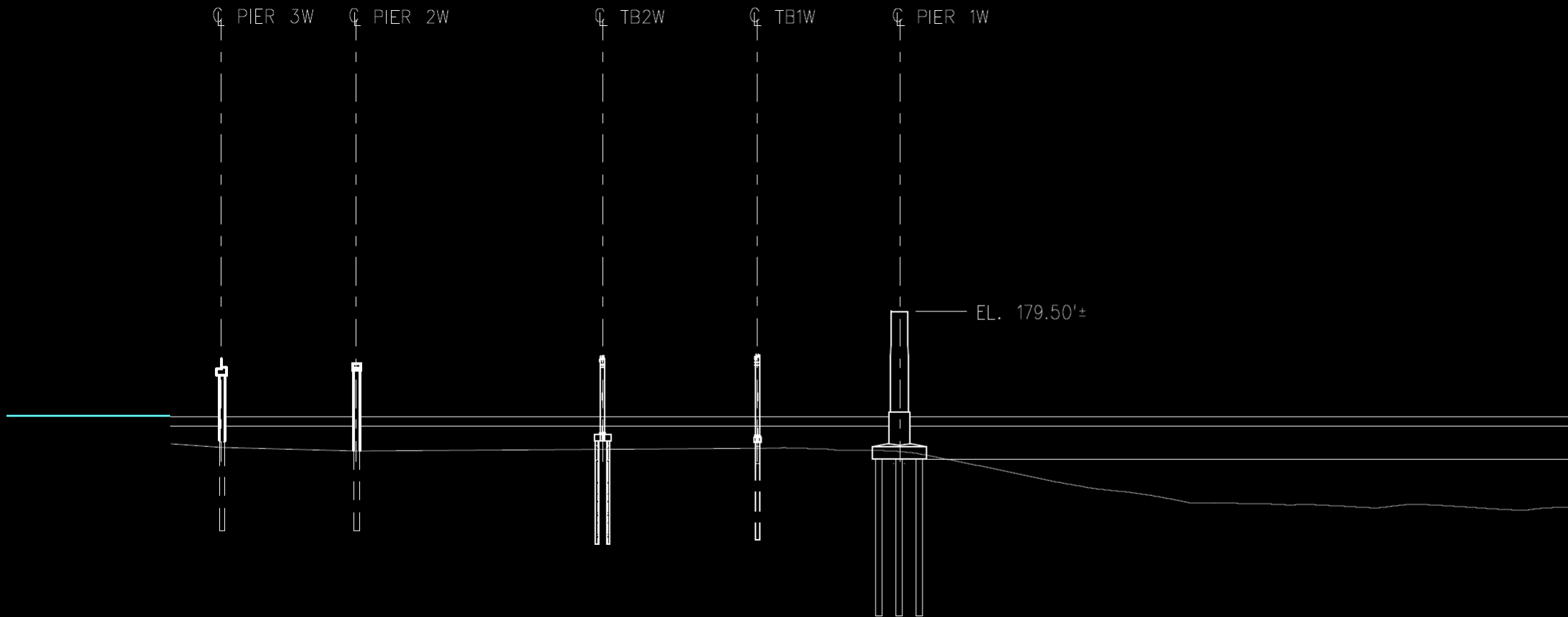
Most effective method to control installation depends on girder type:

- Flexible girder: based on **stay length**
 - ✓ Errors in load assumptions will result in different stay forces but not in girder geometry
 - Requires accurate surveying of as-built structure at each stage to define stay length
 - Stiff girder: based on **stay force**
 - Adjustment of stay length independent of the target force would result in overstressing the cables/girder; shims can be used to correct girder geometry (last resort)

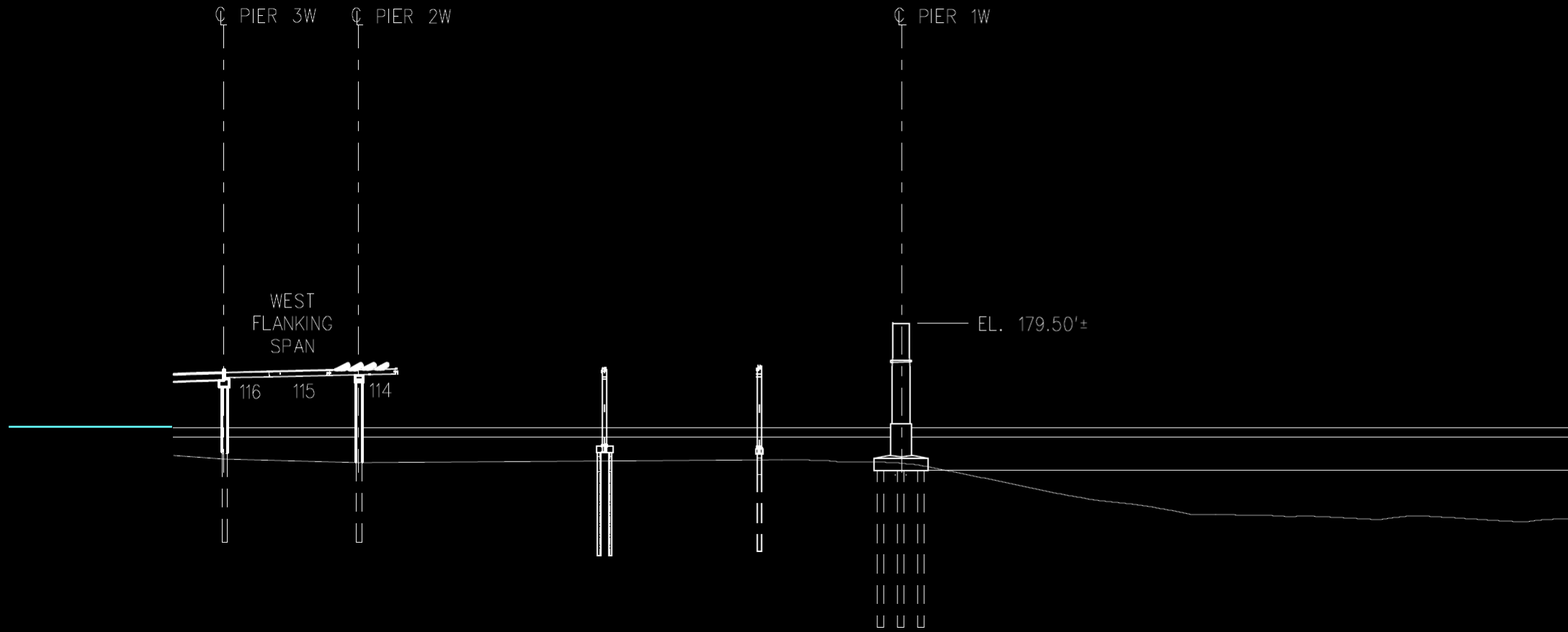
At end of construction, installation within tolerances (among cables and strands) is confirmed by **lift-off tests**, and **final adjustments** are made as needed.



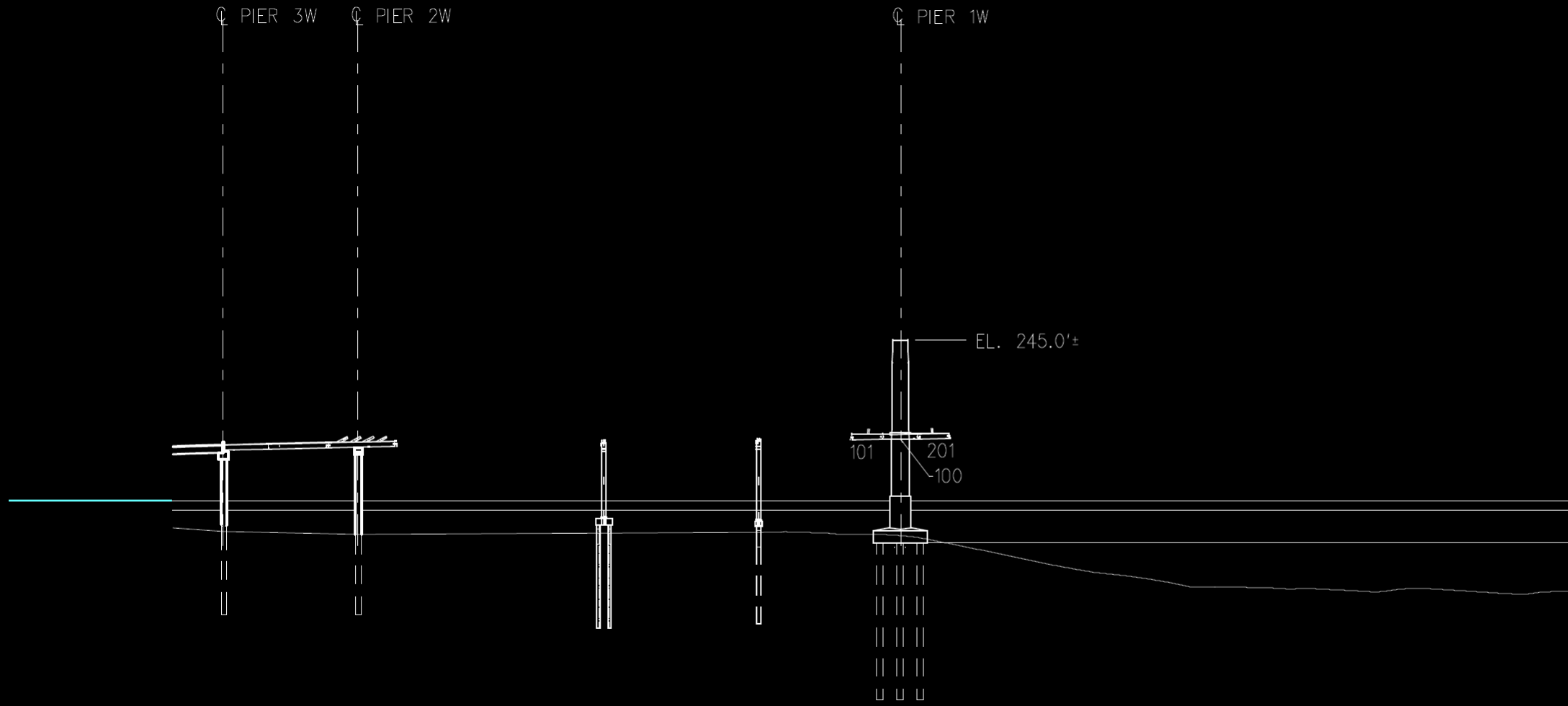
Cable-supported bridges – Cable-Stayed Bridges: **Construction**



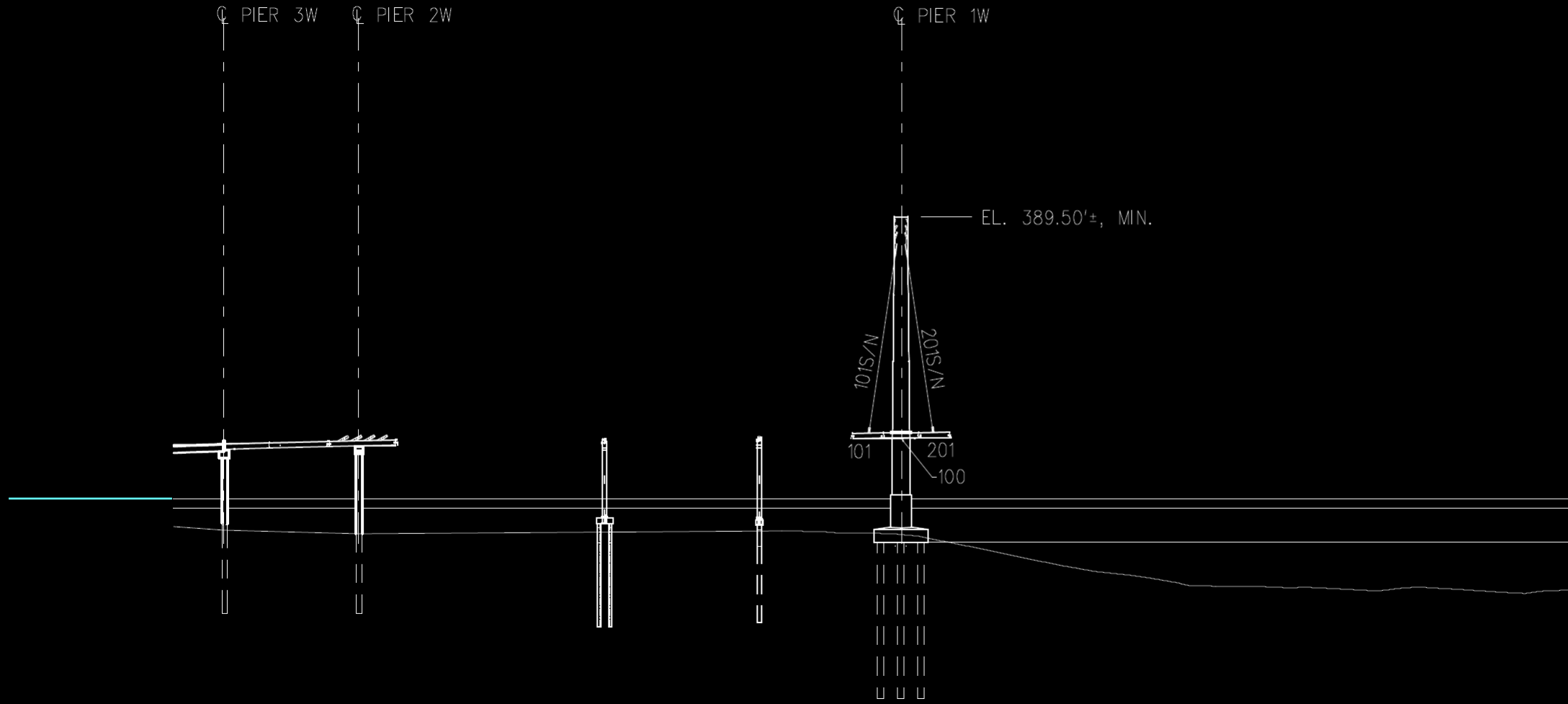
Cable-supported bridges – Cable-Stayed Bridges: **Construction**



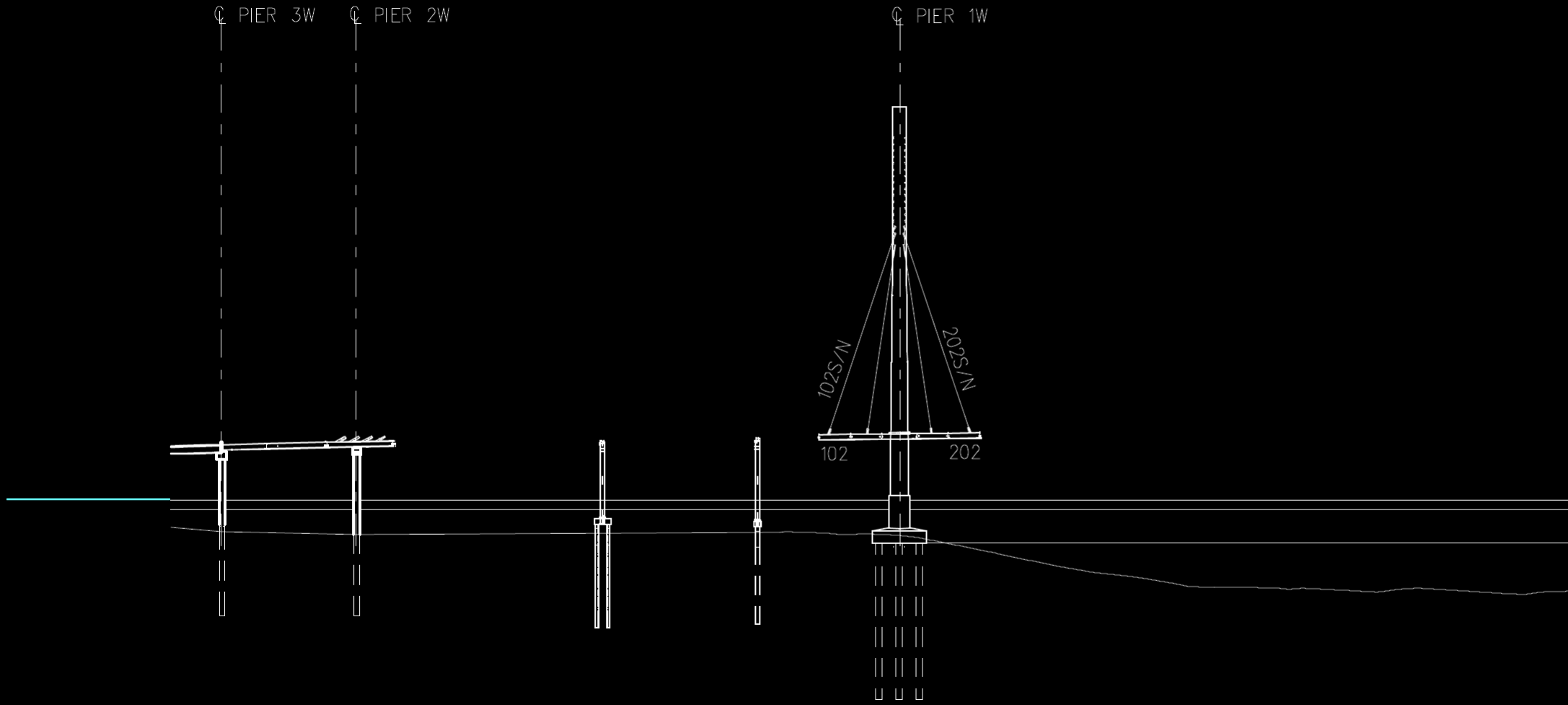
Cable-supported bridges – Cable-Stayed Bridges: **Construction**



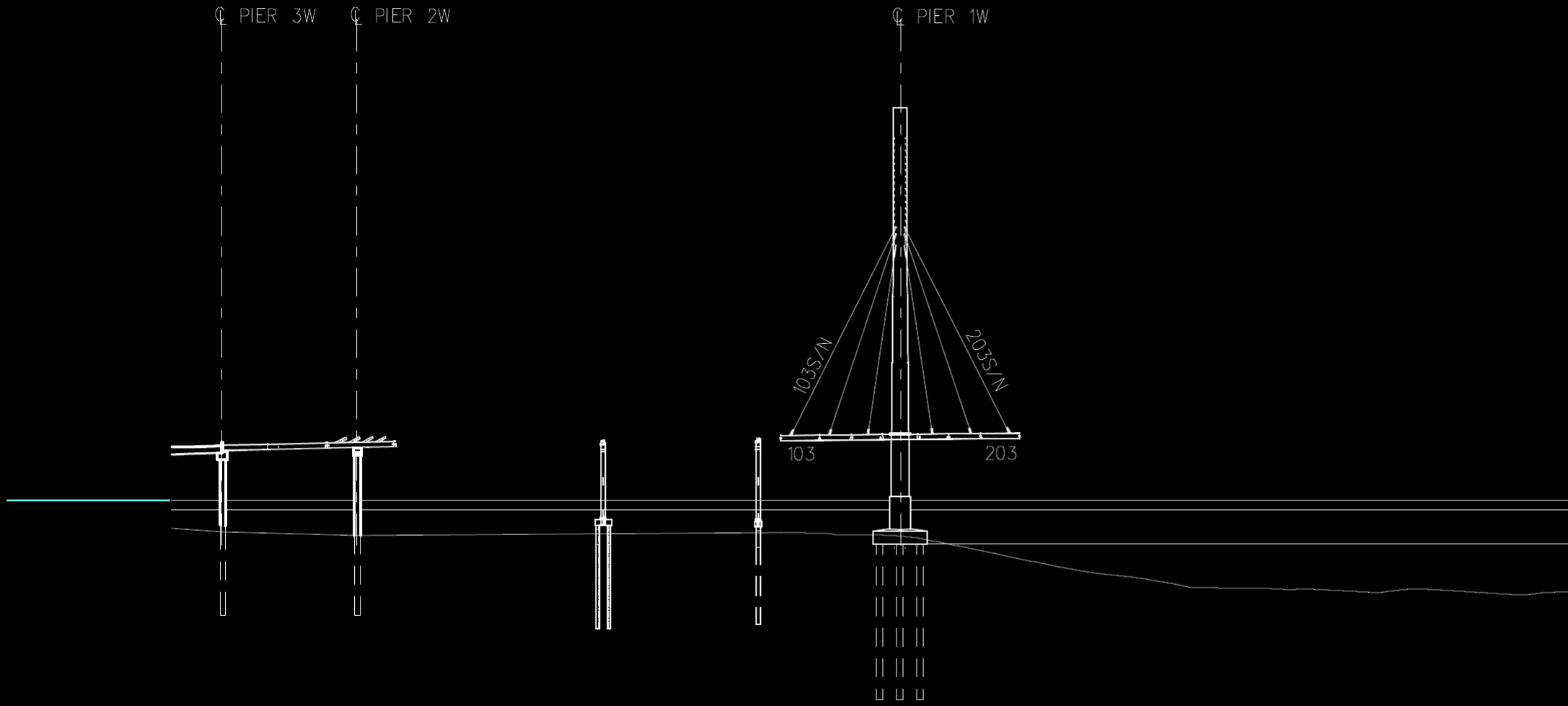
Cable-supported bridges – Cable-Stayed Bridges: **Construction**



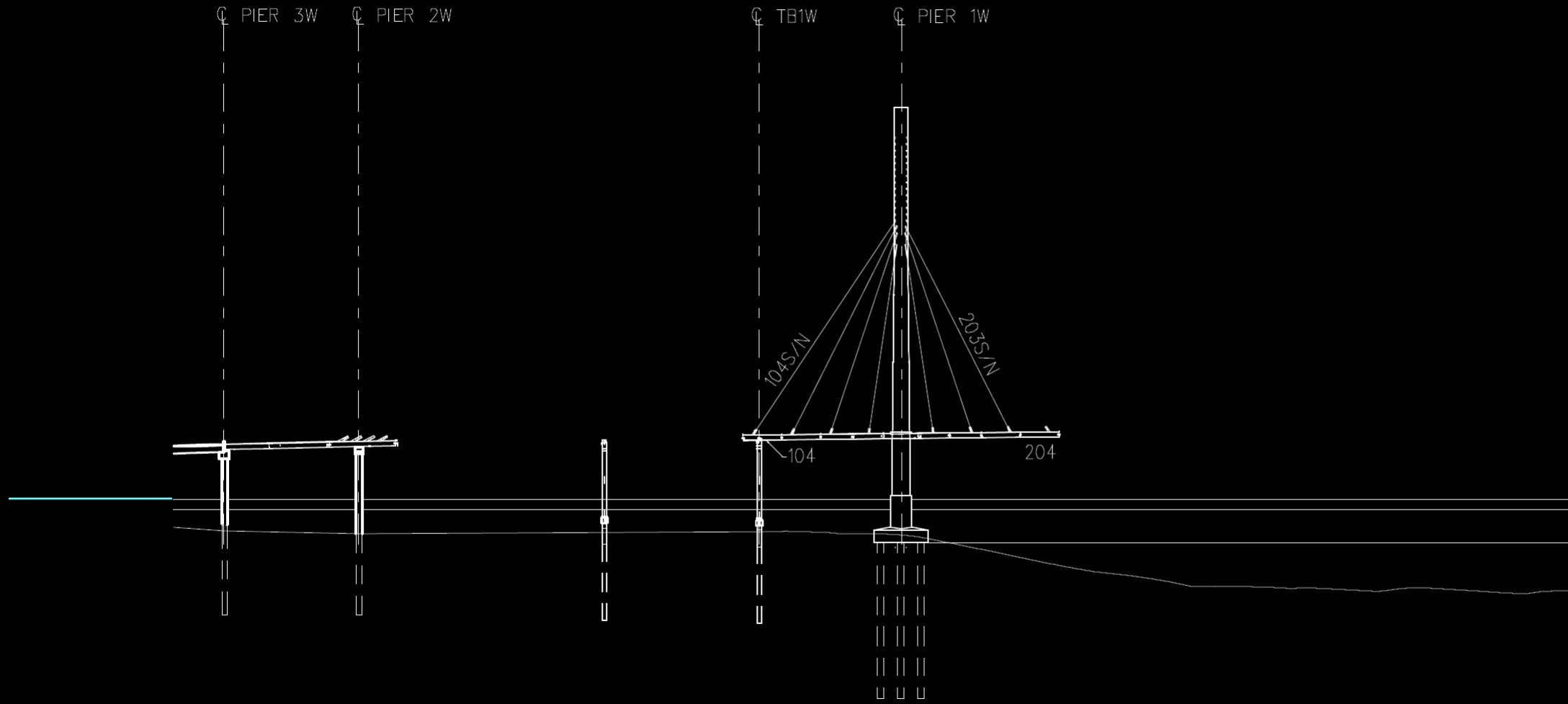
Cable-supported bridges – Cable-Stayed Bridges: **Construction**



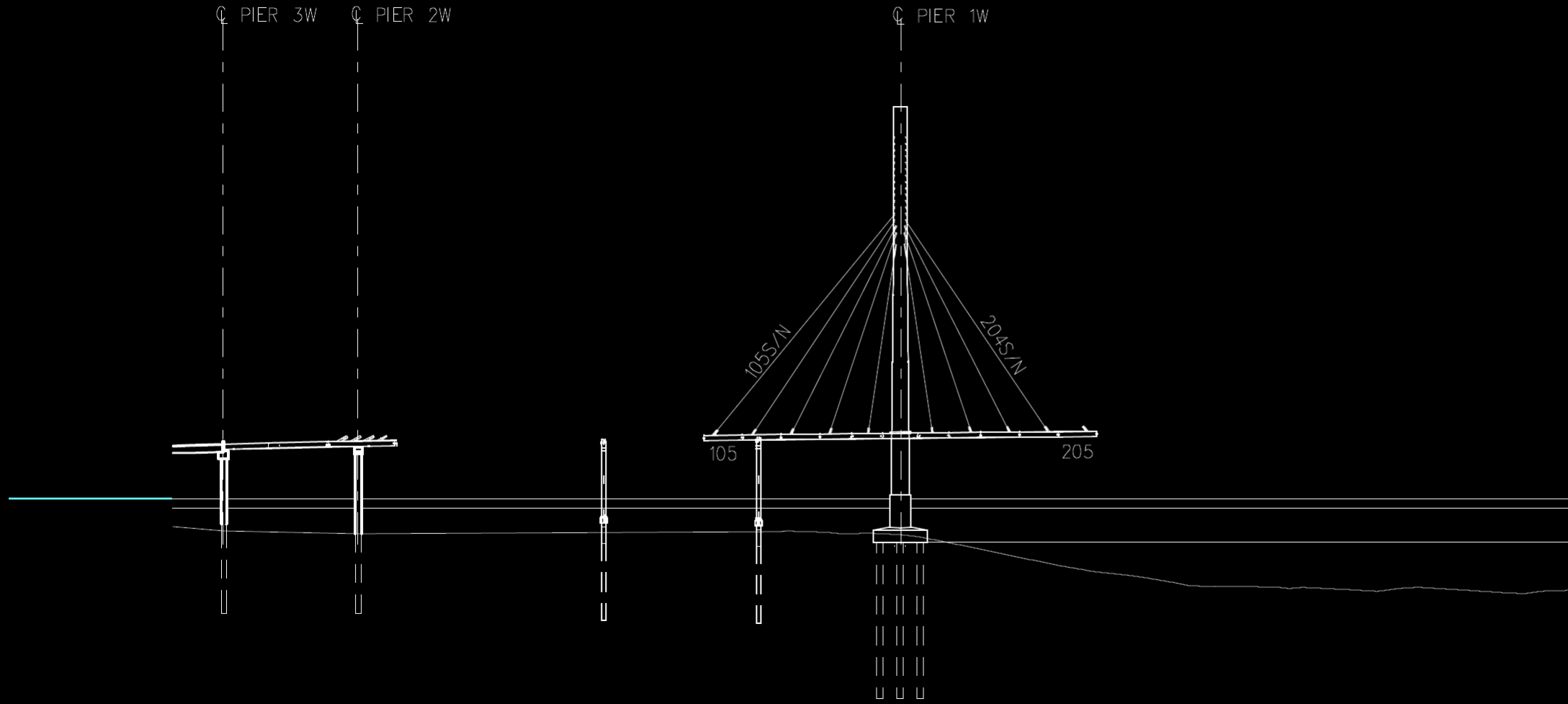
Cable-supported bridges – Cable-Stayed Bridges: **Construction**



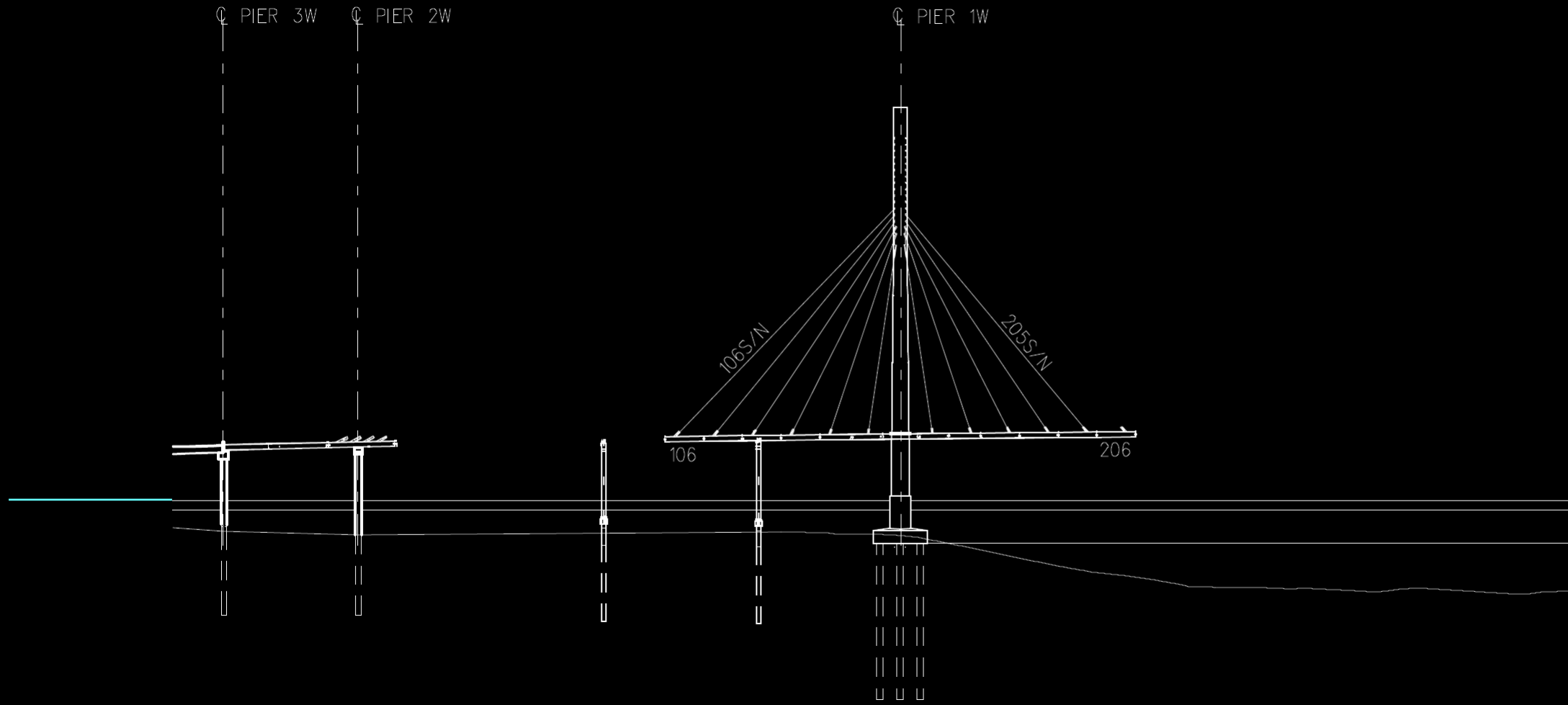
Cable-supported bridges – Cable-Stayed Bridges: **Construction**



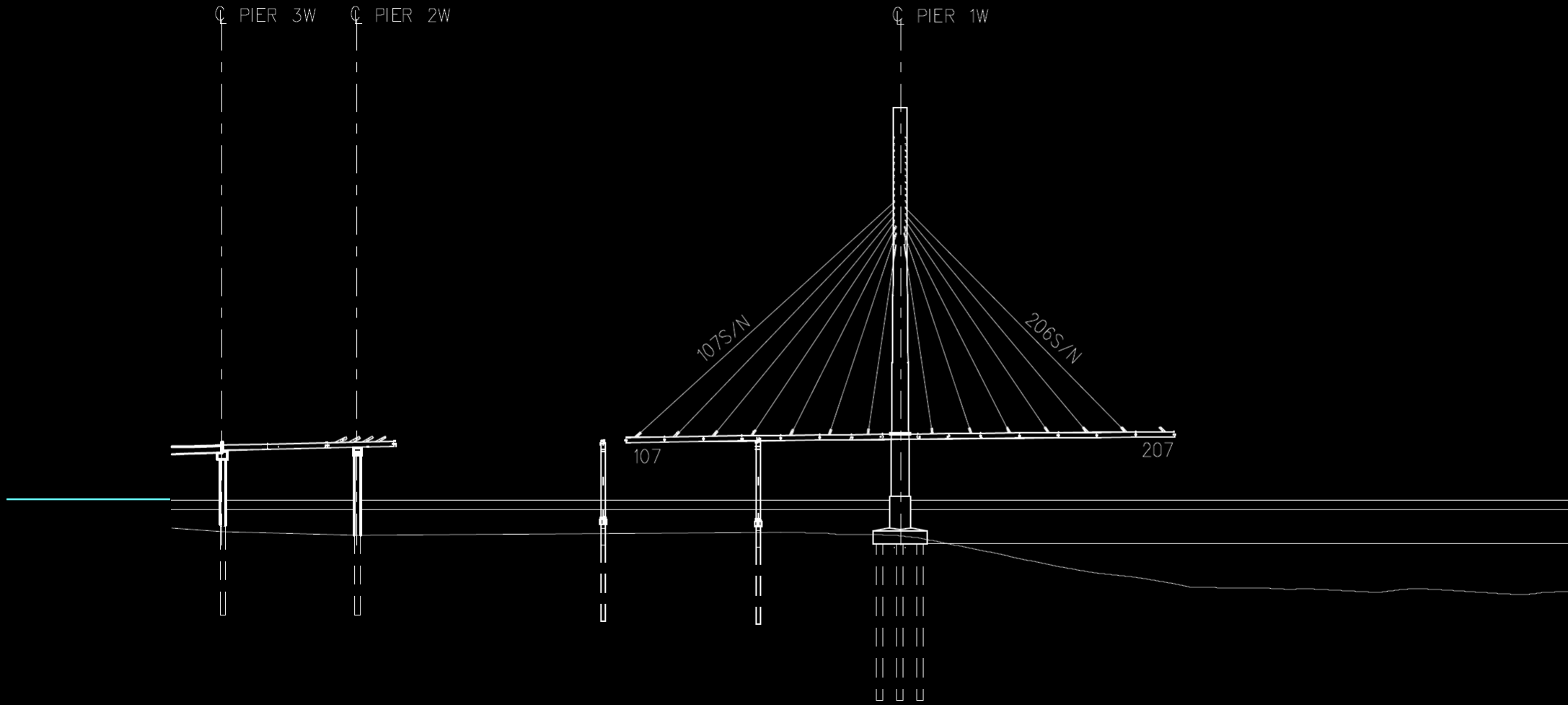
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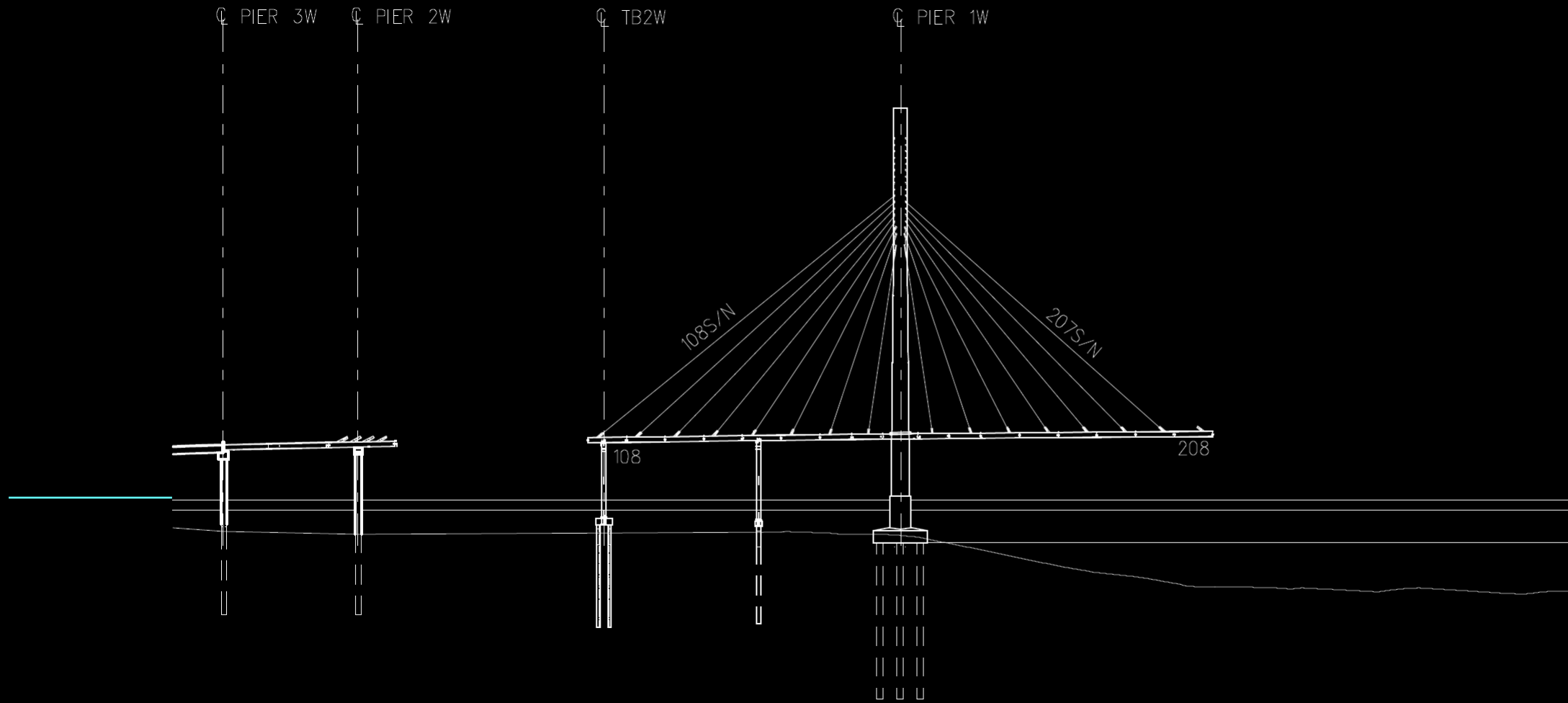
Cable-supported bridges – Cable-Stayed Bridges: **Construction**



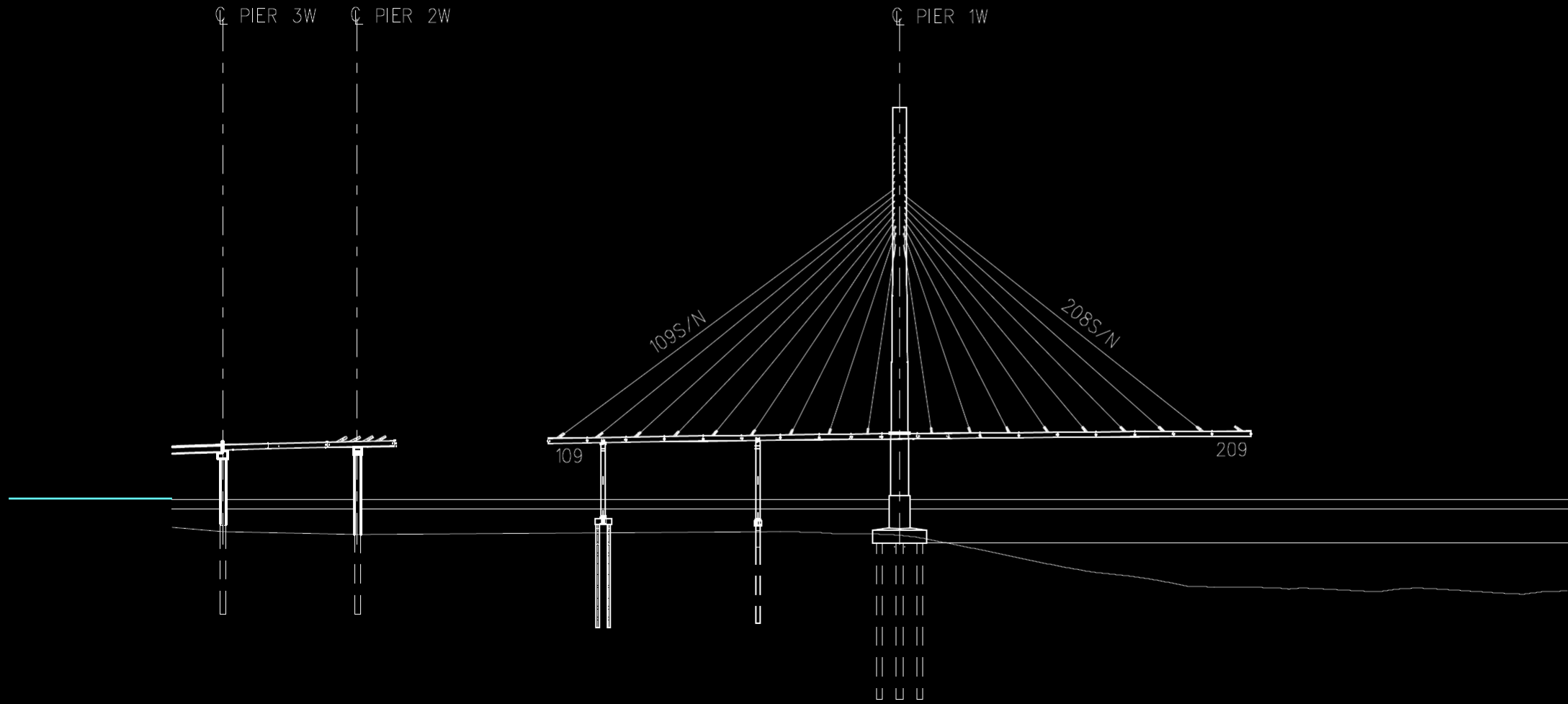
Cable-supported bridges – Cable-Stayed Bridges: **Construction**



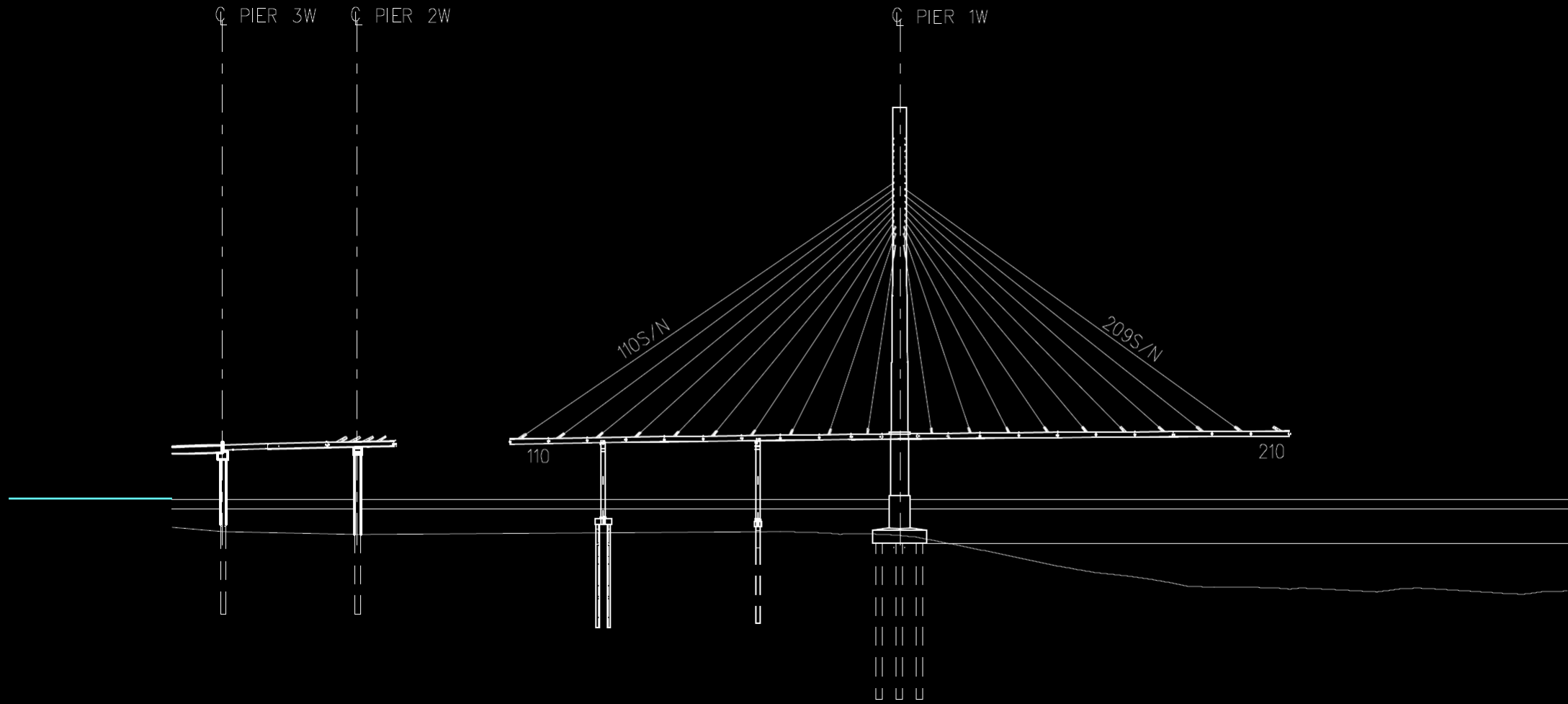
Cable-supported bridges – Cable-Stayed Bridges: **Construction**



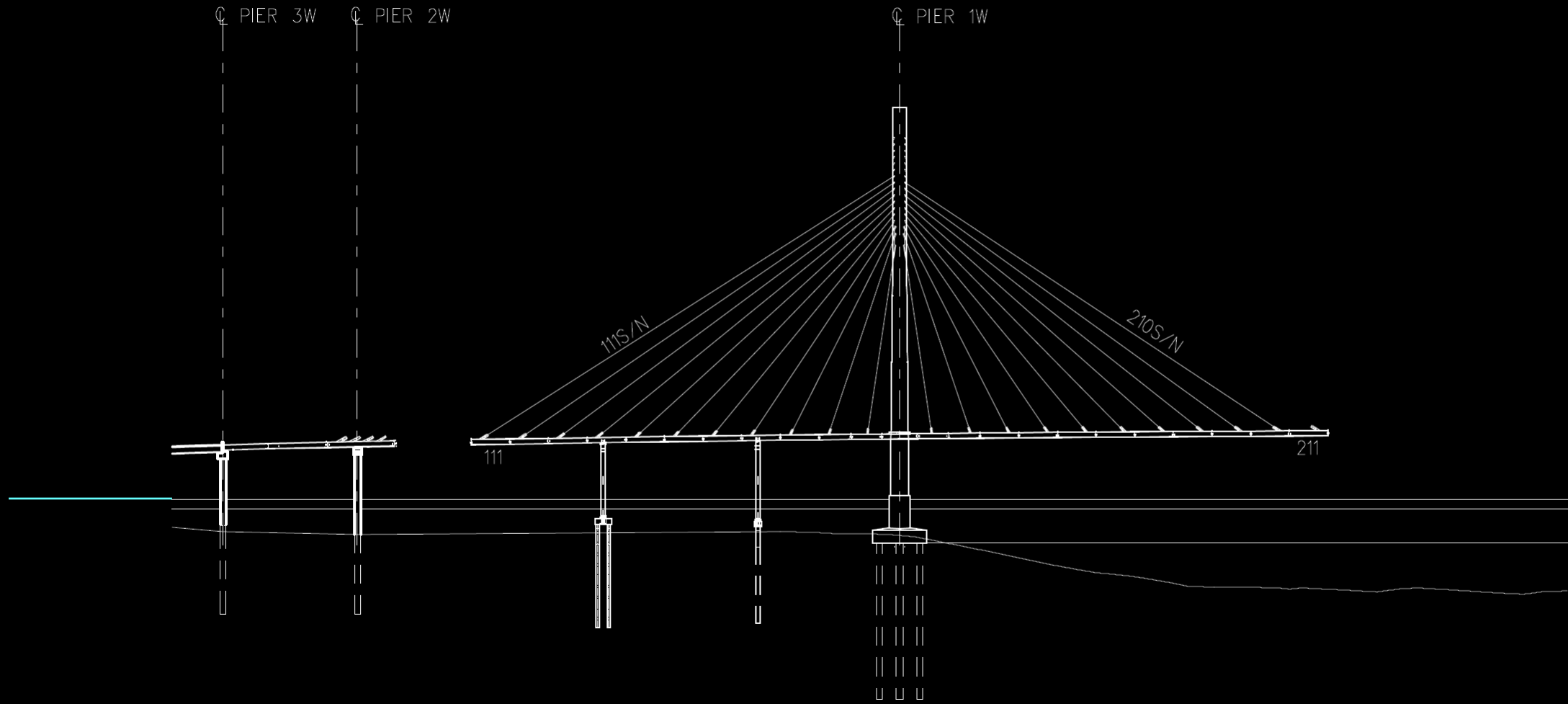
Cable-supported bridges – Cable-Stayed Bridges: **Construction**



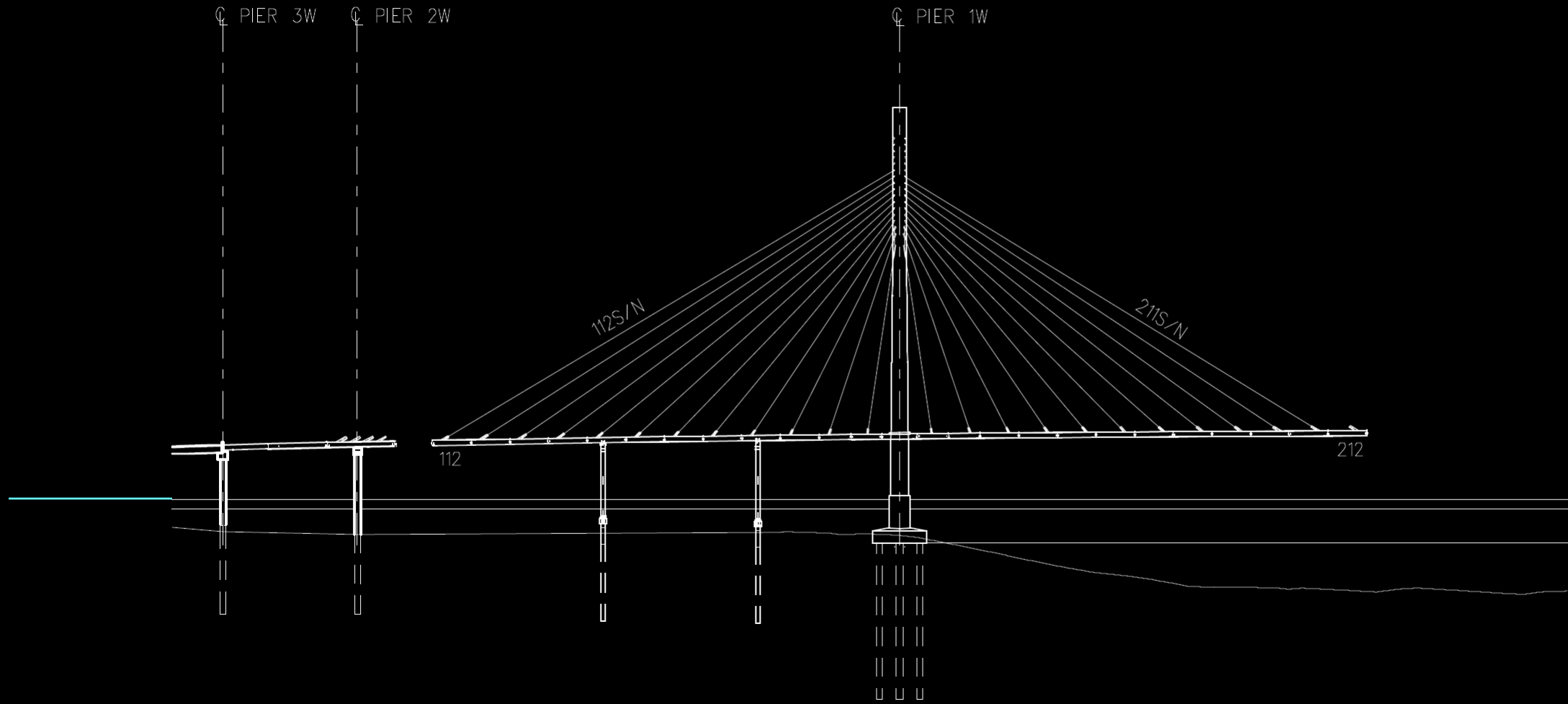
Cable-supported bridges – Cable-Stayed Bridges: **Construction**



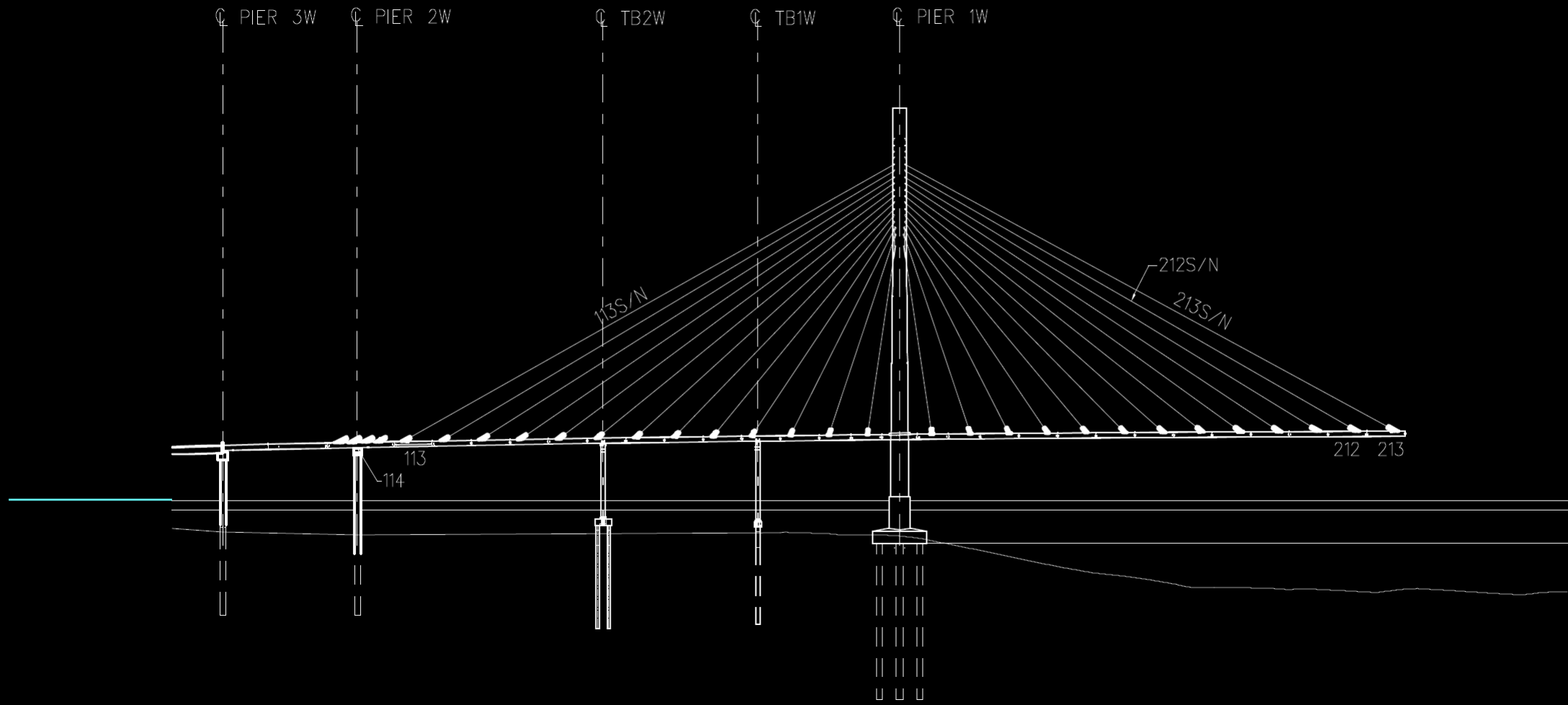
Cable-supported bridges – Cable-Stayed Bridges: **Construction**



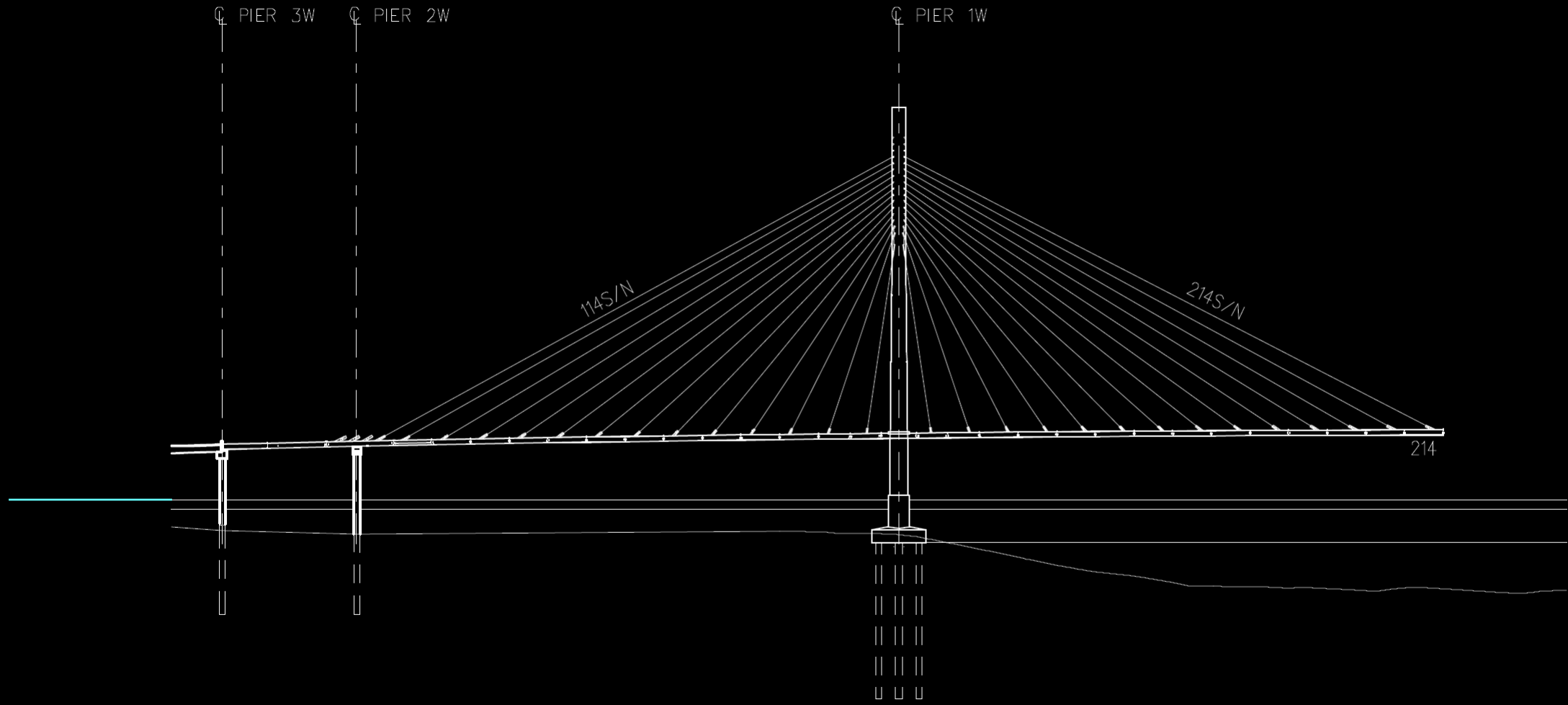
Cable-supported bridges – Cable-Stayed Bridges: **Construction**



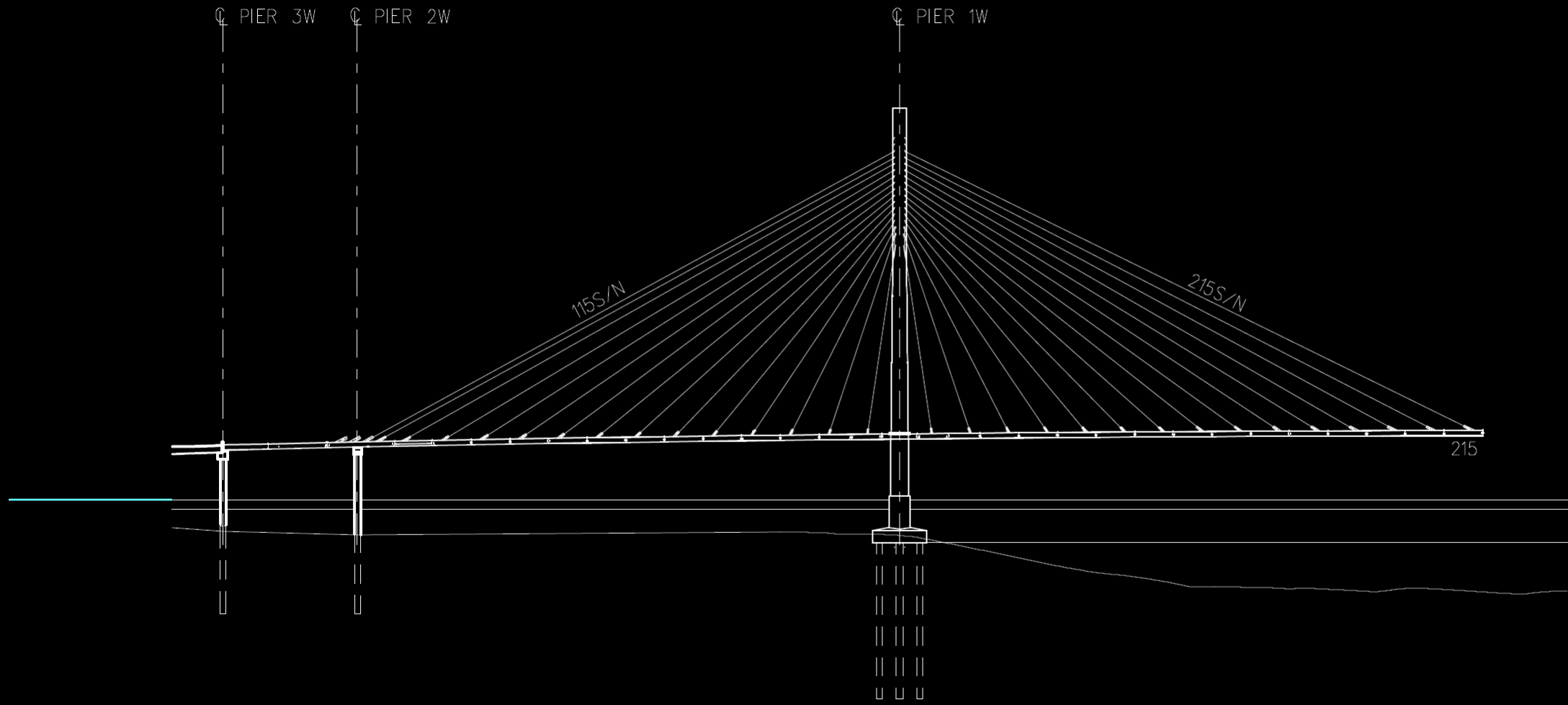
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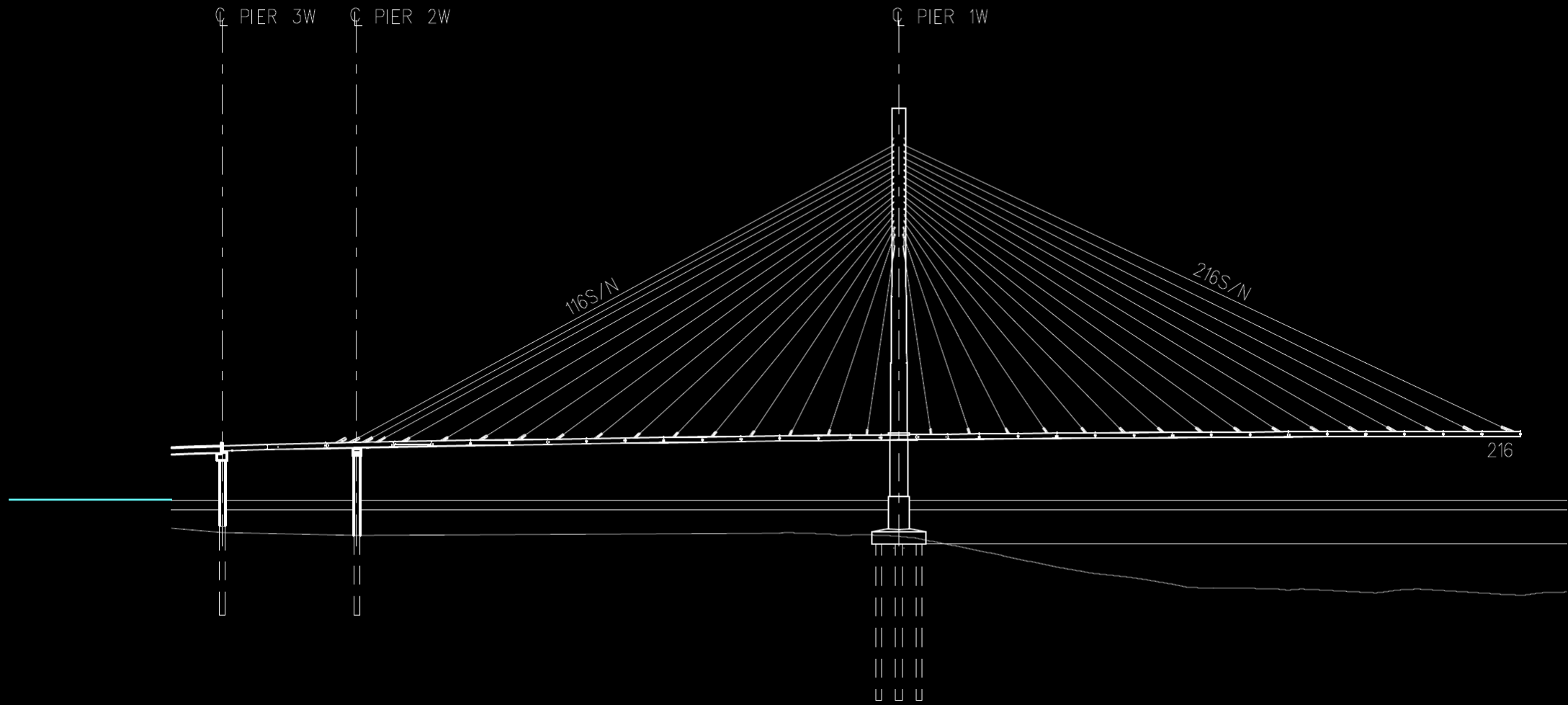
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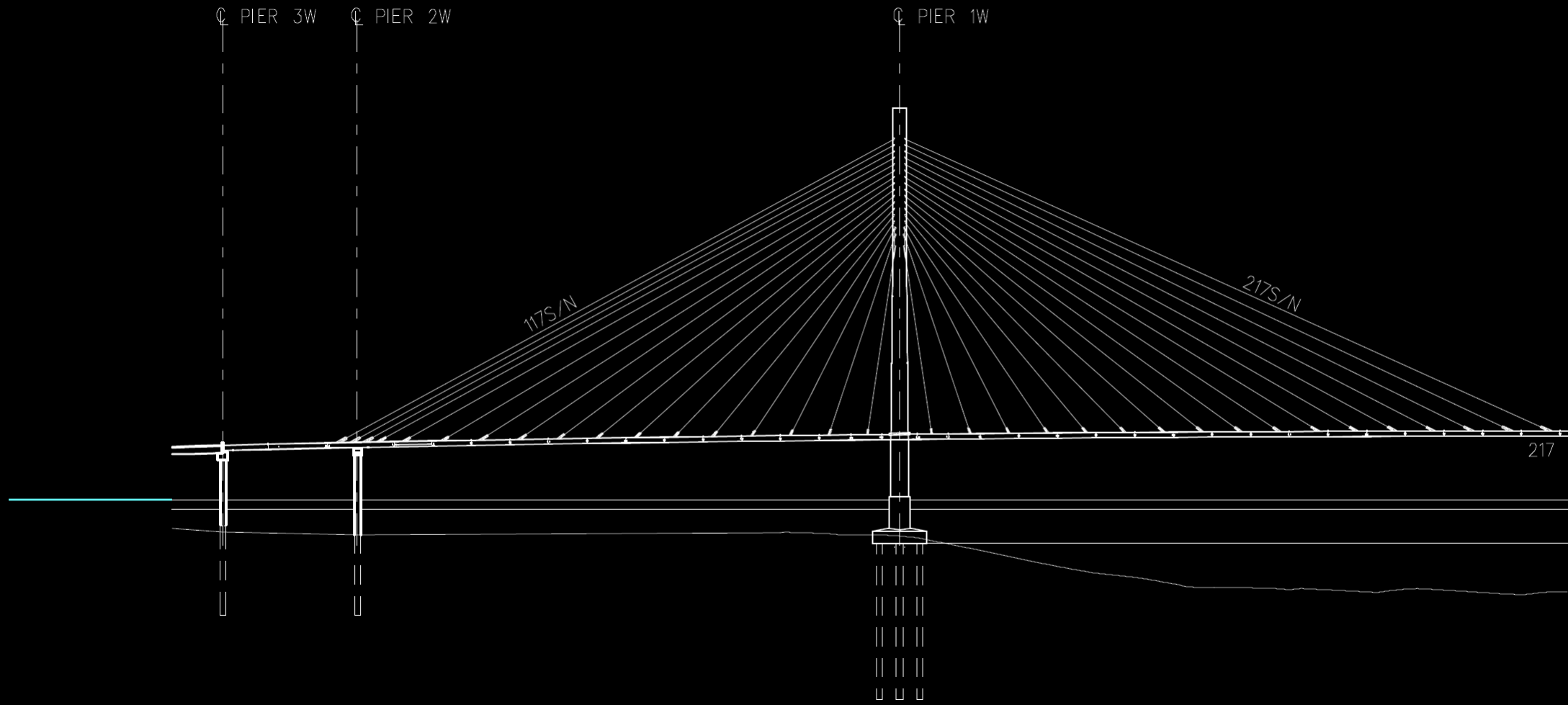
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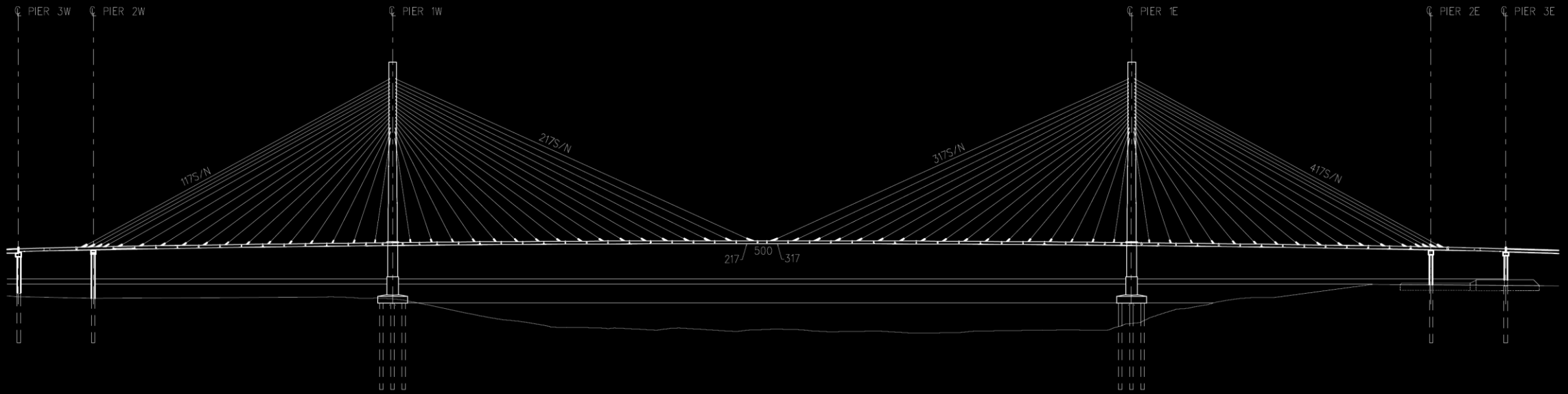
Cable-supported bridges – Cable-Stayed Bridges: **Construction**



Cable-supported bridges – Cable-Stayed Bridges: **Construction**



Cable-supported bridges – Cable-Stayed Bridges: **Construction**



Cable-supported bridges – Cable-Stayed Bridges: **Summary**

Key Takeaways

- CSB most **competitive** typology for a wide range of spans (**200...1000 m**); have gradually replaced truss & arch bridges at the lower end and suspension bridges at the higher end of the range
- The efficiency of the cable-stayed bridge stems from the fact that all members (girder, tower, stay cables) are carrying loads **primarily through axial (normal) forces** and only minimal bending
- The **backstay function** is fundamental to the behaviour of CSB (stiffness, fatigue); in multispan CSB, stiffness is primarily achieved through the towers
- To achieve economy: start with **minimalist solution**, then add features only as needed
- Efficient construction method when **simplicity and repetition/modularity** is achieved; accurate monitoring and record keeping needed to **control geometry**
- **Tall towers** required; often most vulnerable during construction
- Inclined cables are susceptible to **(rain-wind-)vibrations**: provide **surface modifications** to HDPE pipe and **mechanical damping**
- Deck/girders are generally **not replaceable**