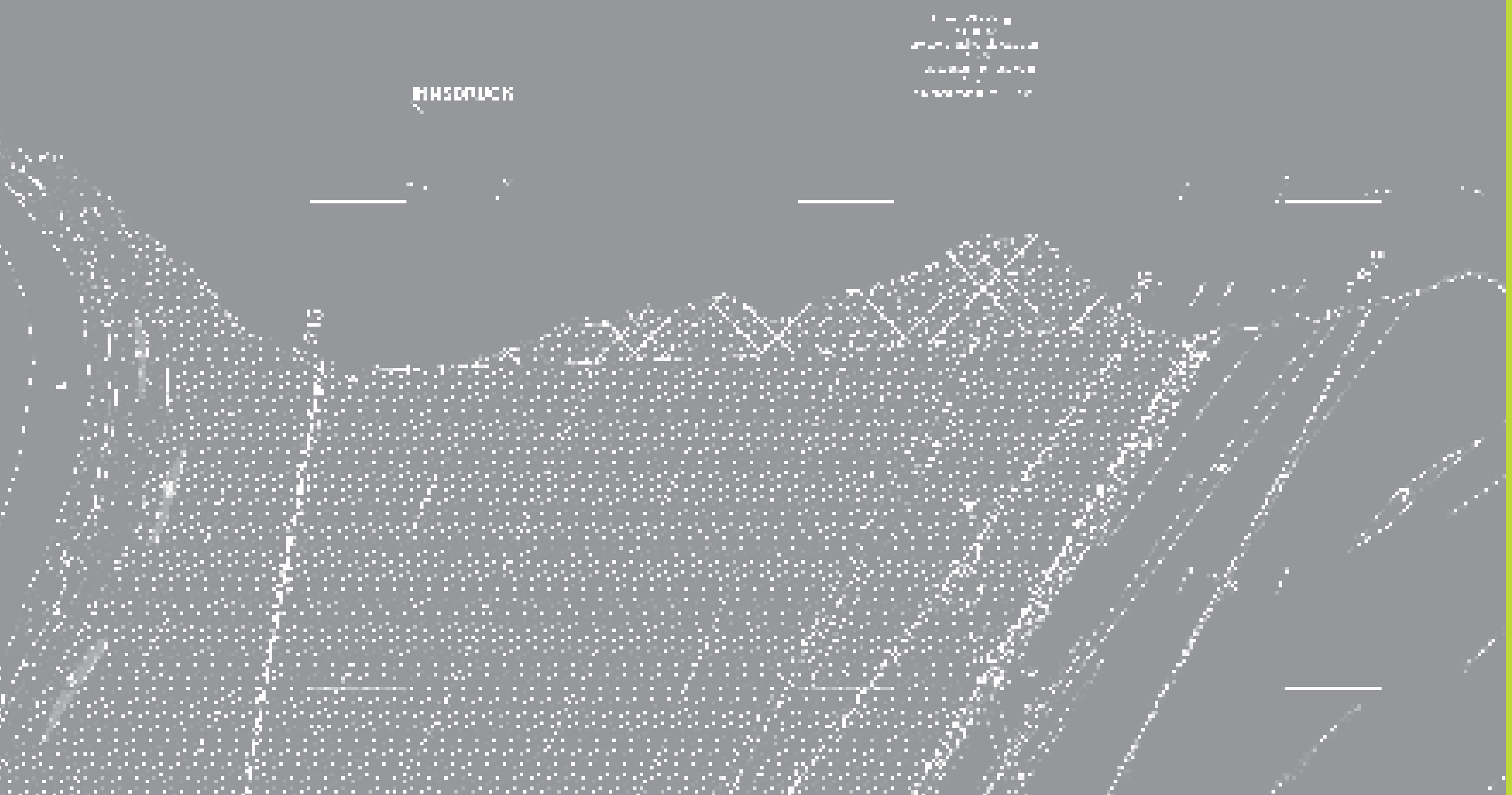
SWS™

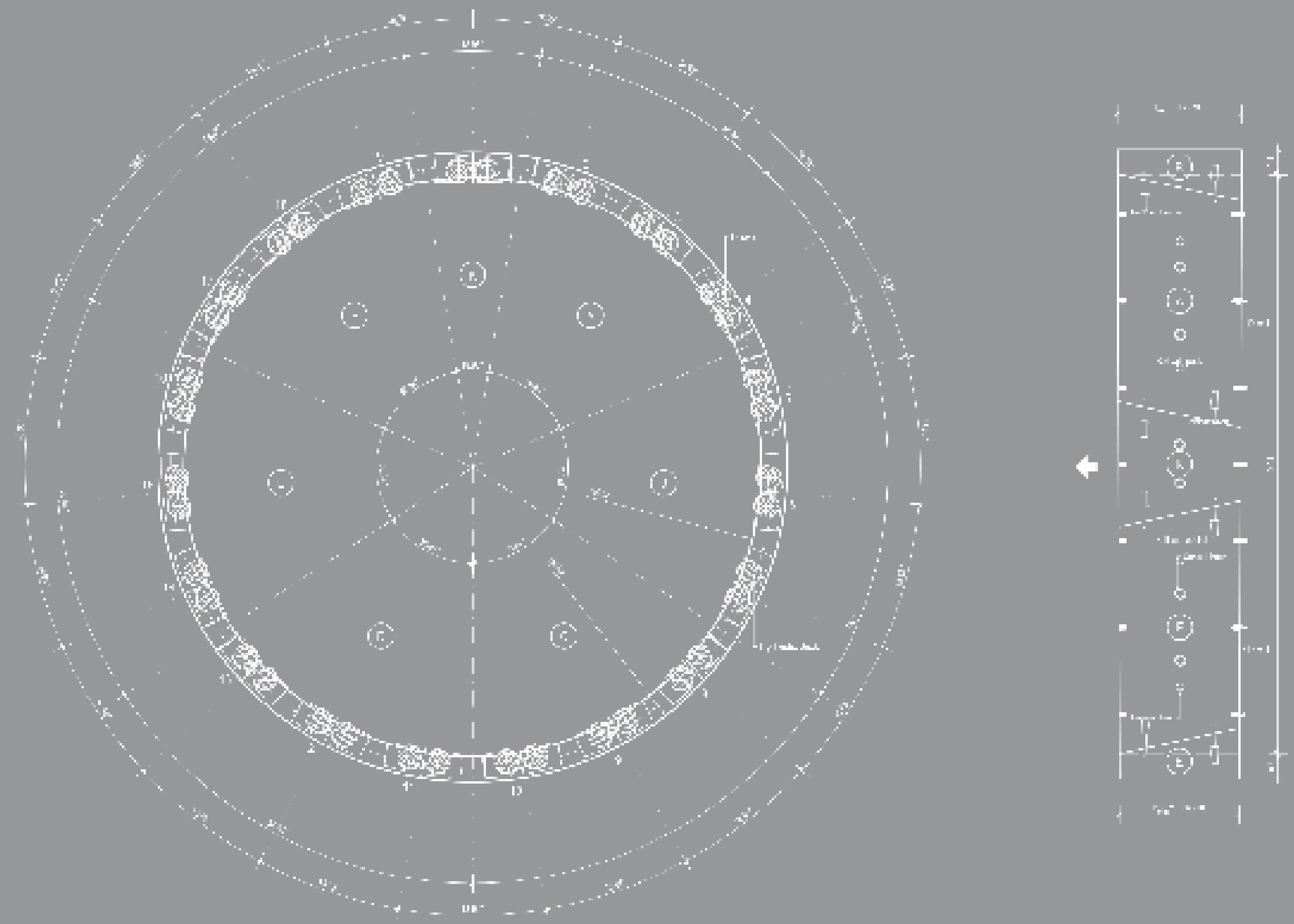
Technical Booklet 01

PRECAST LINING DESIGN



“Our strategy is to escort and ensure our clients with a valuable design which allows to save money and time following the rules of art.
We believe that it is necessary to balance a considered mix of good engineering design with exploration and innovation”

Nima Noroozipour
SWS France Director



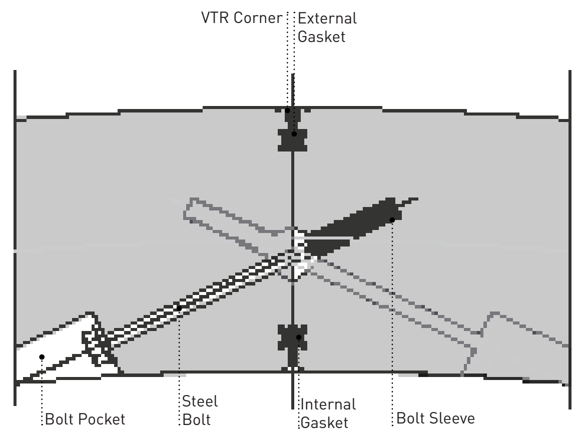
A CHALLENGING DESIGN TASK

Shield tunnel is only apparently a simple construction with solid cylindrical shape; it is in fact an articulated structure made of segments arranged to form consecutive rings in staggered layout.

Segments are usually bolted together at longitudinal joints to make up rings, which in turn are connected via dowels at circumferential joints.

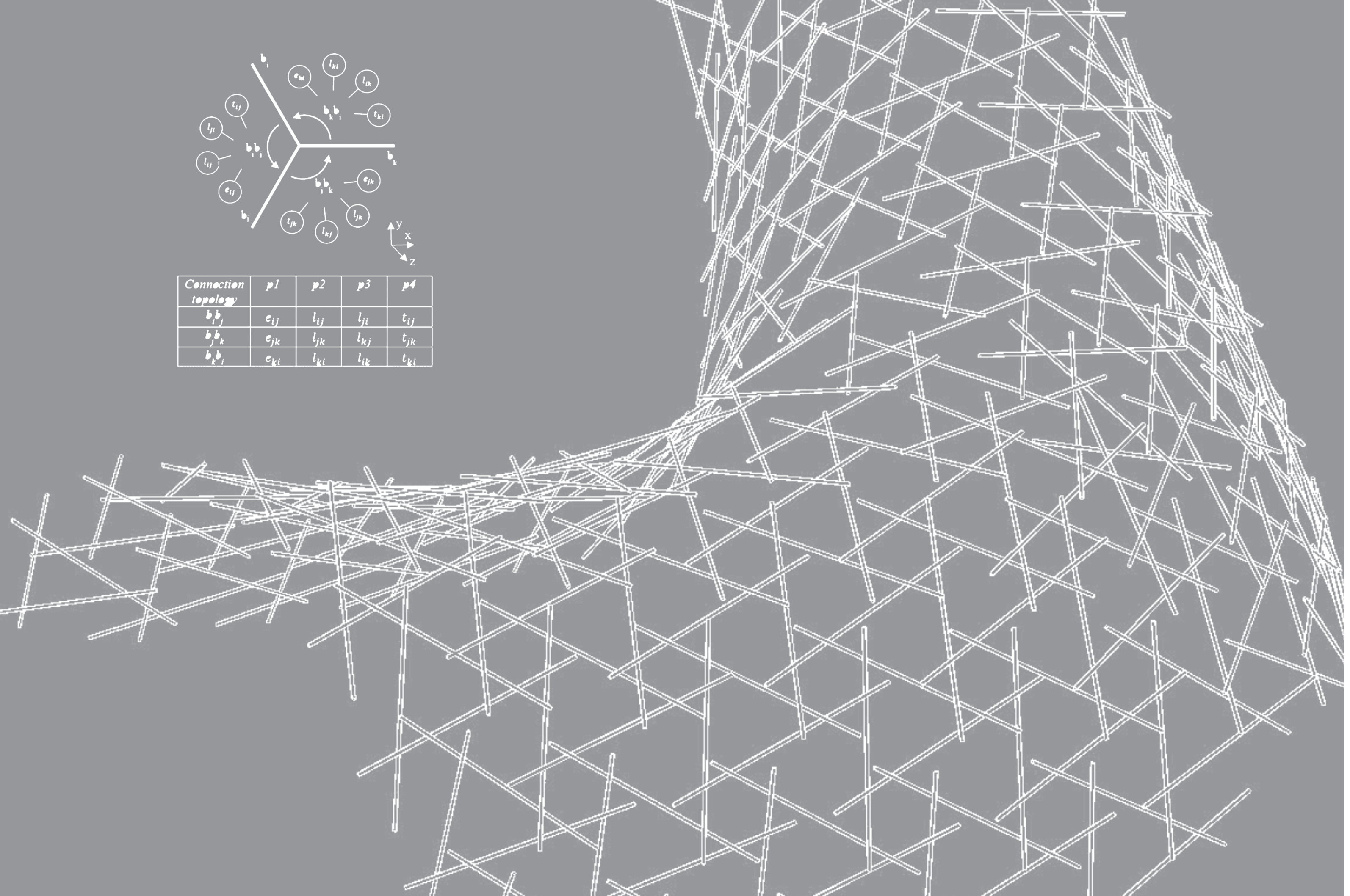
Several modelling techniques exist to account for the presence of joints, each with diverse degree of accuracy: given the repetitiveness of tunnel construction, built as a sequence of multiple rings, even little optimization in the analysis of the single component may lead to significant overall cost reduction.

Mastering the available approaches thus allows tuning the analysis effort to the required design level, in order to satisfy Client's requirements as appropriate.



> ABOVE: TYPICAL DETAIL OF A BOLTED LONGITUDINAL JOINT (BBT project)

> LEFT PAGE: DETAILED REPRESENTATION OF A UNIVERSAL RING (6+1 layout)



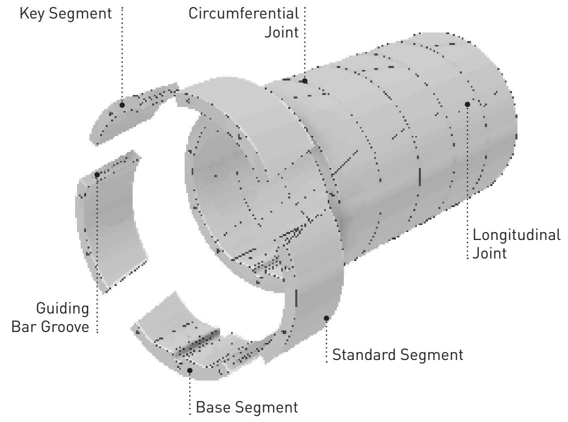
Connection topology	p1	p2	p3	p4
$b_i b_j$	e_{ij}	l_{ij}	l_{ji}	t_{ij}
$b_j b_k$	e_{jk}	l_{jk}	l_{kj}	t_{jk}
$b_k b_i$	e_{ki}	l_{ki}	l_{ik}	t_{ki}

AN ANCIENT STRUCTURAL CONCEPT

Although precast tunnel lining is a modern construction technique, the underlying structural concept is much less recent.

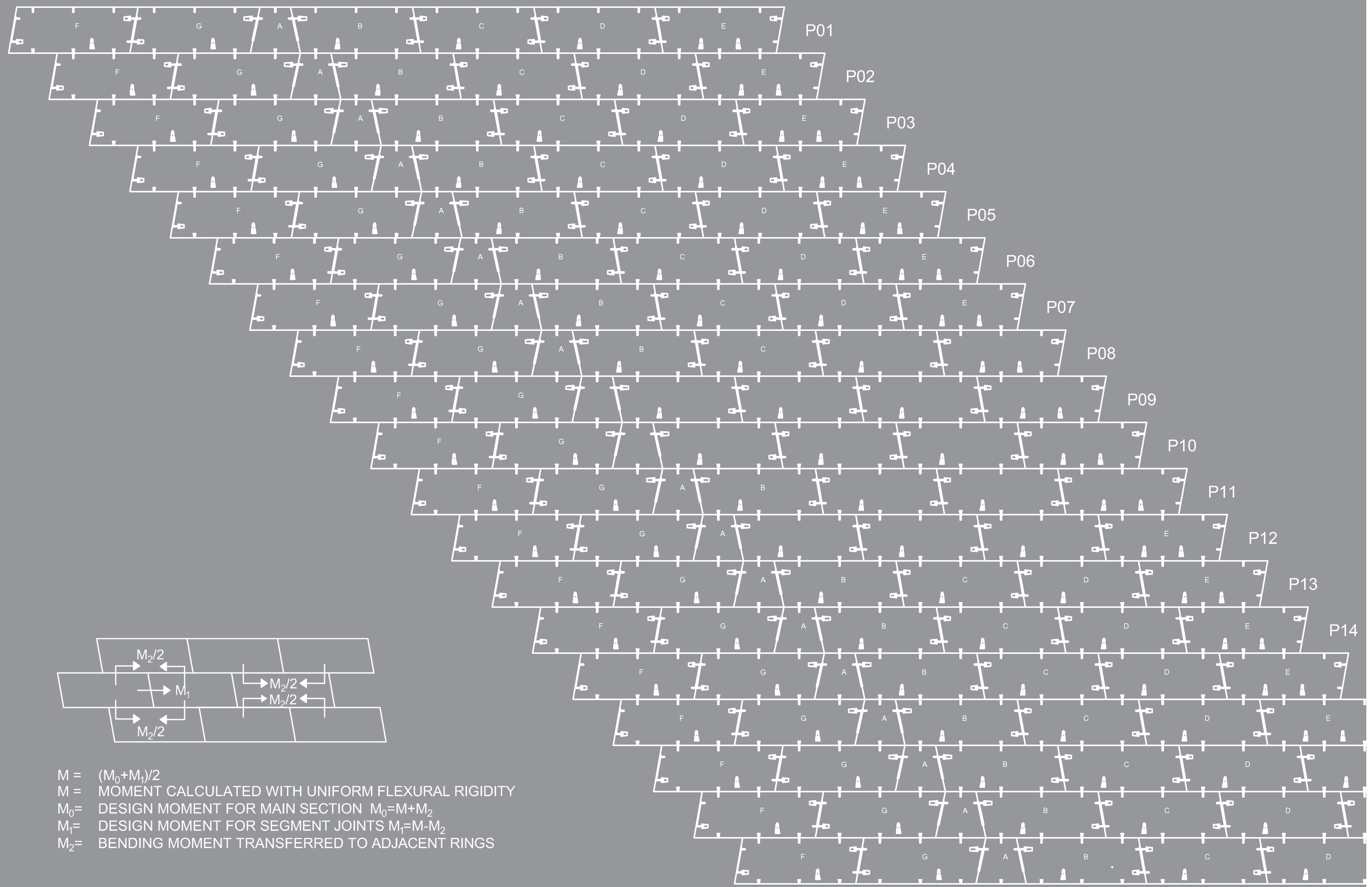
In fact, tunnel rings are arranged in a staggered layout to prevent longitudinal joints being in the same position, and this configuration allows mutual force transfer between rings, typical of 3D reciprocal frame. These structures date back to Mesopotamian Era and have been further studied by Leonardo da Vinci.

Rationale of tunnel lining reciprocity is that single rings with internal hinges (i.e., longitudinal joints between segments) are inherently unstable.
Only the connection of multiple rings makes the tunnel statically determinate, provided the joints are staggered, otherwise the entire tunnel becomes unstable.



> ABOVE: CONCRETE LINING INVENTOR MODEL (KOVALINCH project)

> LEFT PAGE: TRI RF-UNITS RECIPROCAL STRUCTURE CONCEIVED BY LEONARDO DA VINCI



TRADITIONAL
DESIGN APPROACH

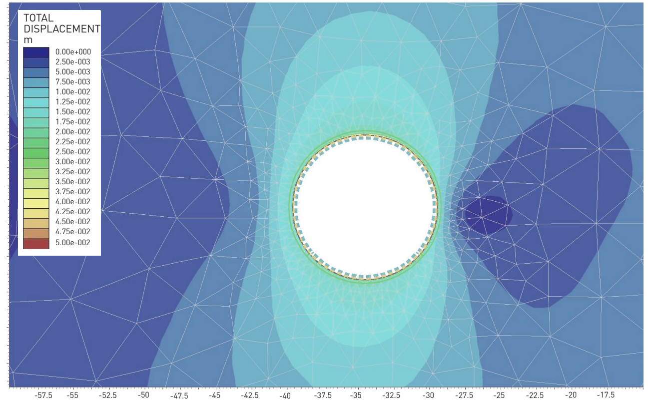
For years, tunnel linings have been studied as solid rings with uniform flexural rigidity, thus ignoring the localized stiffness decrease at longitudinal joints.

This simplification allowed the development of analytical solutions, under specific loading conditions, and is generally able to provide safe design for tunnel segments.

The "solid ring" approach is in fact widely present in technical Standards and Guidelines, and refined by Muir Wood [1] via the introduction of a reduction coefficient for bending stiffness (an equivalent rigidity of the entire lining can reflect the reduction of rigidity at segment joints).

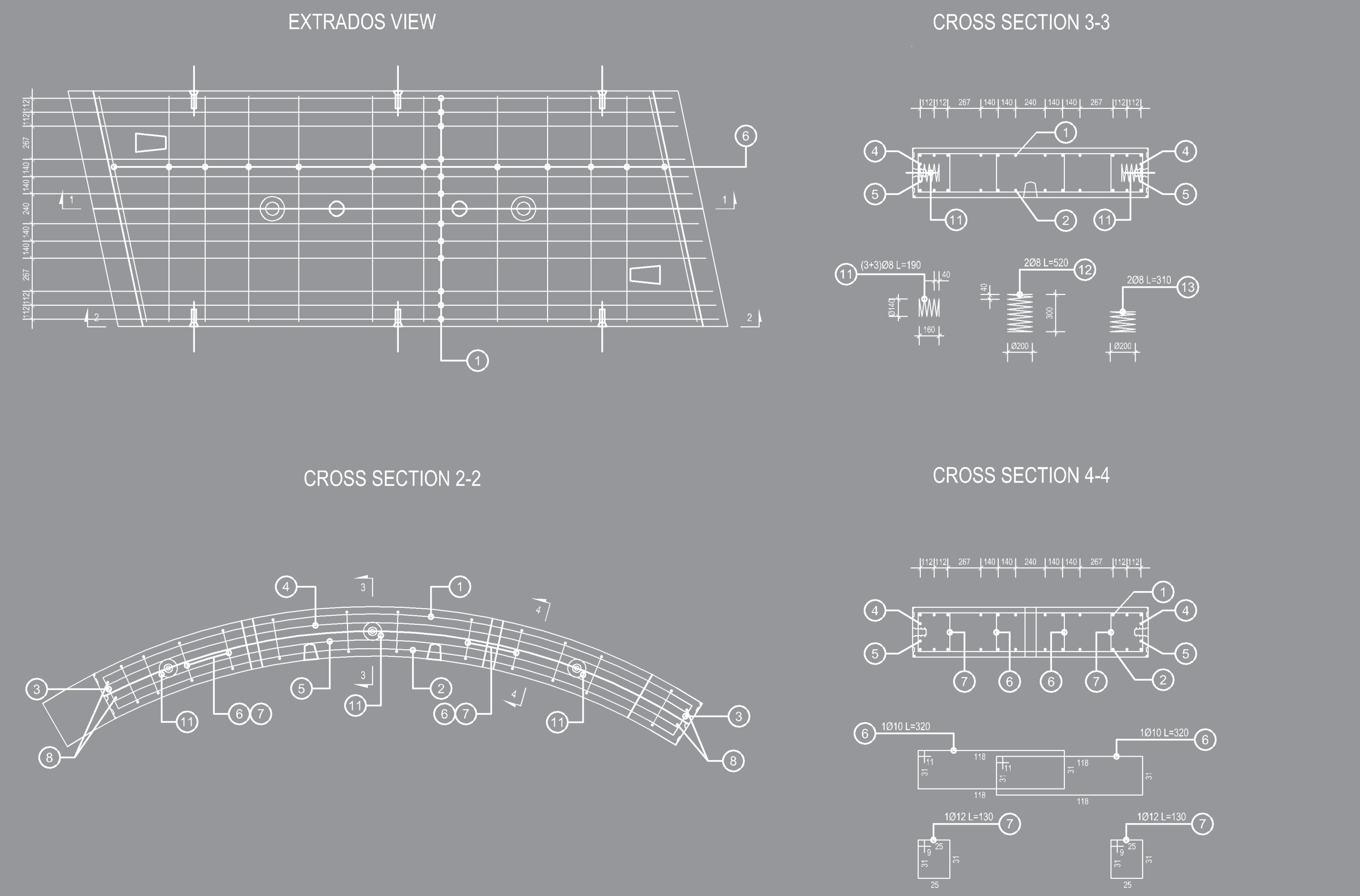
This traditional approach is still valid for many applications, but does not allow a precise definition of section force distribution between segments and joints, which may be required for specific needs and, in general, for design optimization.

[1] Muir Wood - The circular tunnel in elastic ground (1975)



> ABOVE: RS² MODEL DEVELOPED FOR A MECHANISED TUNNEL (BBT project)

> LEFT PAGE: ALLOWABLE TUNNEL JOINT LAYOUT AND MOMENT TRANSFER MECHANISM



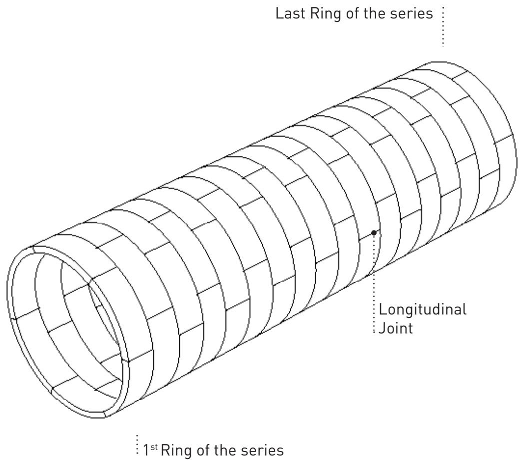
ADVANCED DESIGN APPROACH

As a logical evolution of the traditional approach, actual joints between segments and rings are included in the analysis.

For instance, Japanese Standards [1] describe "multi-hinged ring models" and "beam-spring models": the former simulate longitudinal joints as perfect hinges; the latter include rotational springs for joints between segments and shear springs for joints between rings.
Although yielding evident improvement, these advanced approaches are far from being exhaustive as neglect the presence of friction and mechanical fasteners or require at least correct tuning of spring stiffness.

A further, possibly ultimate, evolution in tunnel design approaches may be the actual modelling of contact surface and the presence of mechanical fasteners, thus avoiding undesired analysis simplifications and definition of complicated adjustment techniques for spring stiffness.

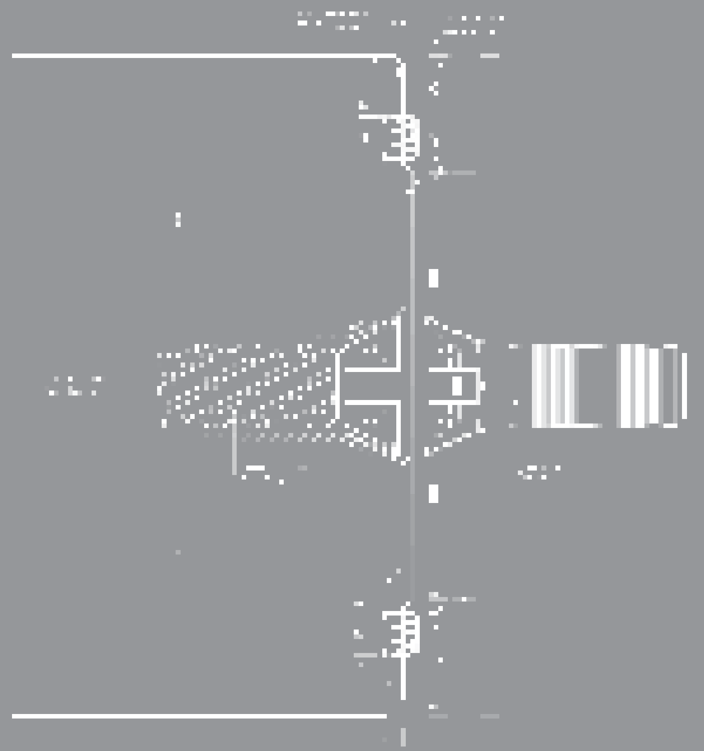
[1] Japan Society of Civil Engineers - Standard Specifications for Tunneling: Shield Tunnels



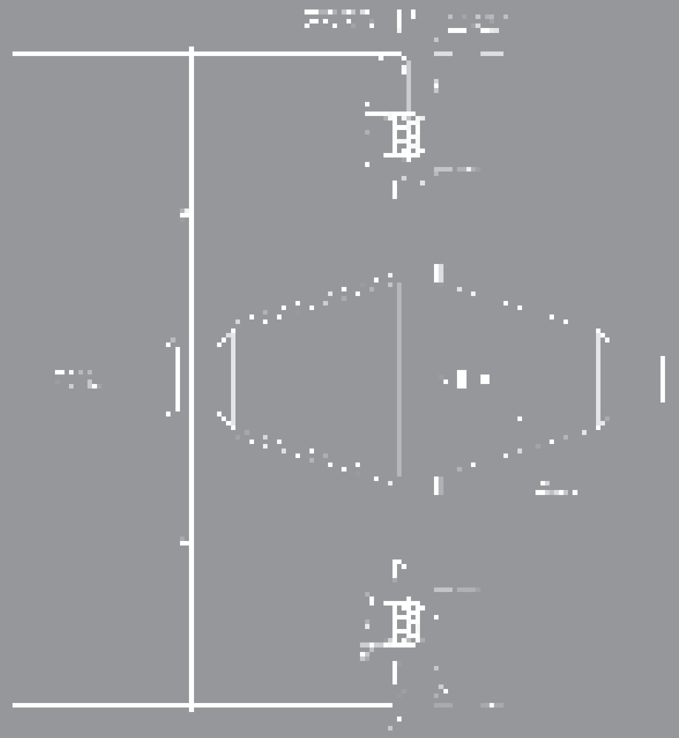
> ABOVE: TUNNEL 3D FE MODEL WITH STAGGERED RING LAYOUT (STRAND 7)

> LEFT PAGE: TYPICAL REINFORCEMENT LAYOUT OF A TUNNEL SEGMENT

CIRCUMFERENTIAL JOINT WITH SPECIAL DOWEL



CIRCUMFERENTIAL JOINT WITH BICONE SHEAR DOWEL



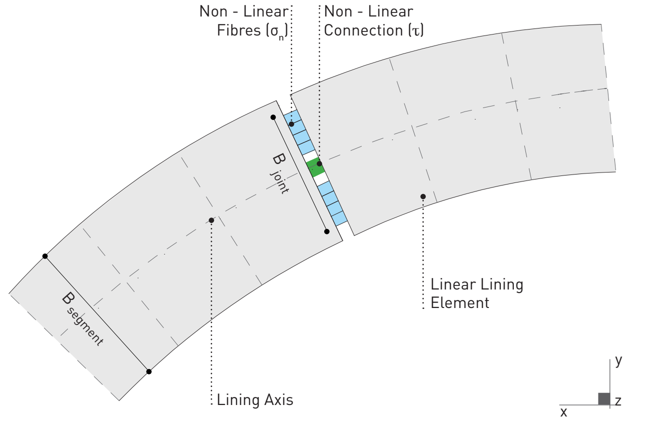
NON-LINEAR JOINT BEHAVIOR

SWS followed this design evolutionary path until developing a modelling approach that simulates the actual non-linear joint behaviour.

The reduced contact surface between segments, due to gasket grooves and stress relieves, is modelled via "fibre elements" characterised by concrete nonlinear stress-strain relationship: in case of large thrust eccentricity in the ring, the contact surface further decreases as fibres in tension are progressively excluded by the solver.

Shear force transfer is modelled by friction at contact elements and eventually by bolt and guiding rod elements, if present. Connection between consecutive rings is simulated via dowel elements.

Inclusion of these technological components, with their respective stress-strain relationships, allows non-linear models to provide correct section force and deflection distribution along the ring and gives insight into the local performance of tunnel devices.



> ABOVE: SCHEMATIC OF SWS MODELLING APPROACH FOR LONGITUDINAL JOINTS

> LEFT PAGE: TYPICAL DOWEL CONNECTORS IN CIRCUMFERENTIAL JOINTS

ACHIEVED ADVANTAGES

SWS design method allows optimization of precast segment design because, unlike simplified approaches, the actual distribution of forces between segments and joints is accounted for, without need for spring stiffness tuning required by codified advanced approaches.

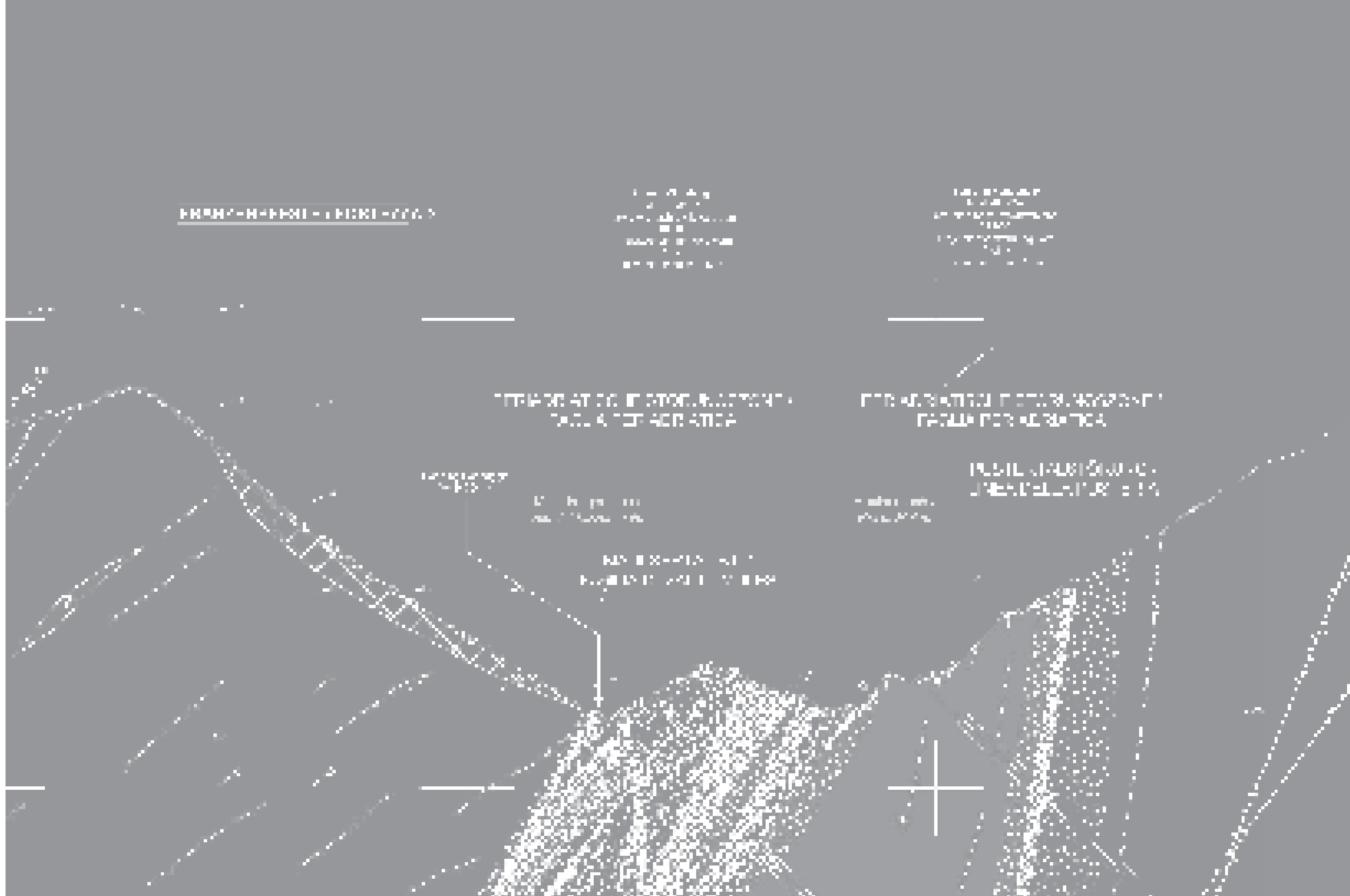
Furthermore, forces in the mechanical fasteners and guiding rods between segments are directly determined by the solver, making their check straightforward.

Longitudinal joint check against compressive stress in the contact surface is automatically verified by convergence of non-linear analysis.

Finally, detailed modelling of contact surface provides strategic information on the pressure distribution within longitudinal joints, necessary to evaluate gasket water tightness and overall tunnel sealing performance.

SIMPLIFIED DESIGN APPROACH	SWS DESIGN APPROACH
APPROXIMATE EVALUATION OF JOINTS PERFORMANCE	ACCURATE EVALUATION OF JOINTS PERFORMANCE
▽	▽
CONSERVATIVE FORCE CALCULATION POTENTIALLY RESULTING IN NON-REQUIRED BOLTS INSTALLATION	DESIGN OPTIMISATION POTENTIALLY LEADING TO NO BOLTS INSTALLATION
APPROXIMATE ESTIMATION OF CONCRETE LINING WATER TIGHTNESS	ACCURATE CALCULATION OF CONCRETE LINING WATER TIGHTNESS

> ABOVE: SCHEMATIC COMPARISON BETWEEN SIMPLIFIED AND SWS DESIGN APPROACHES



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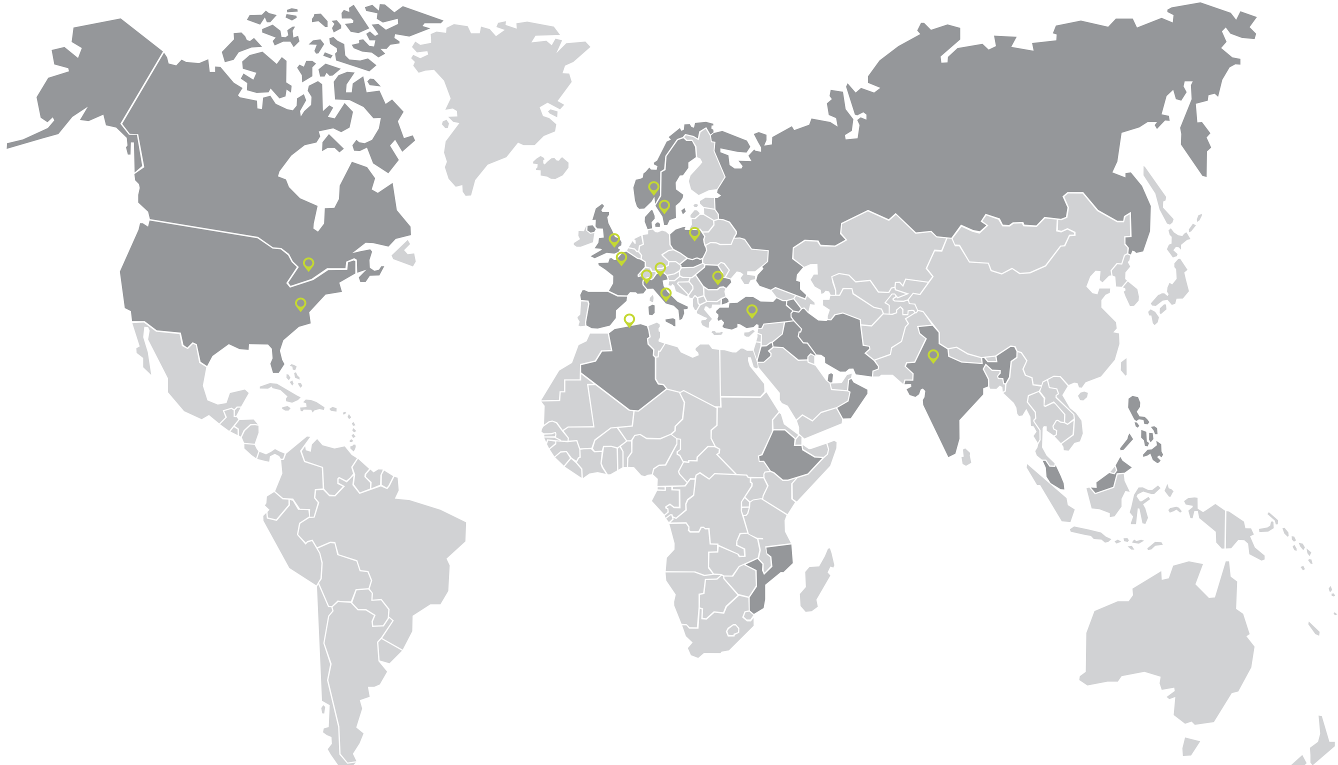
North America



SWS Engineering S.p.A.
Via della Stazione 27, 38123 Trento, Italy
Via Luigi Robecchi Brichetti 6, 00154 Roma, Italy
Corso Marconi 10, 10121 Torino, Italy

SWS Engineering France
34, rue de l'Abbé Groult
75015 Paris, France

SWS Engineering UK LTD
16 Upper Woburn Place
WC1H 0BS, London, UK

SWS Engineering Poland
ul. Tuwima 28, p. 518
90-002 Łódź, Poland

SWS Engineering Romania
București, sector 5
Calea Rahovei, no. 266-268, Romania

SWS Global Mühendislik (Turkey)
Mahatma Gandhi Cad. 26/3
GOP, Çankaya, Ankara, Turkey

SWS Global Engineering India Pvt Ltd
Office No 519, 5th Floor
DLF Tower A, Jasola, New Delhi – 110025

SWS Engineering Norway NUF
Bispegata 13
Oslo, Norway

SWS Engineering Sweden
Ängelholmsvägen 42
Båstad, Sweden

SWS Engineering Algeria
Local 3 et 4, Coopérative Cnat Hannachi,
Rue Chahid Said Chahat Bayes, Dar El Beida, Algeria

SWS Canada Consultants LTD
478 Huron Street, Suite #200,
M5R 2R3 Toronto (ON), Canada

SWS Engineering USA Inc.
888 17th St NW STE 1000
Washington, DC 20006

Shnabel - SWS
12720 Hillcrest Road
Dallas, TX 75230

For more information: sales@swsglobal.com

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www.swsglobal.com