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Advanced Aspects & Precautions in Tunnel Linings Constructed by NATM Using Gantries

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Abstract: Tunnel linings constructed using the New Austrian Tunnelling Method (NATM) rely heavily on gantry-mounted formwork systems to achieve accurate geometry, safe access, and efficient concrete placement in highly variable ground conditions. Unlike mechanized methods such as TBM, NATM involves sequential excavation, evolving ground profiles, and continuous adjustments to temporary support-factors that make gantry behaviour far more sensitive to alignment, stability, and operational errors. This paper examines advanced aspects of NATM tunnel gantry operation, focusing on concrete workability, vibration effects, offset control, sway behaviour, curve negotiation, gantry length considerations, and the growing integration of automated systems such as shotcrete robots and expandable gantries. A detailed evaluation of construction-stage failures-including bulk-end blowouts, crown cavities, honeycombing, turnbuckle plate deformation, panel discontinuity, inadequate skin and runner plate stiffness, welding defects, kicker beam cracking, and improper kinematic performance-is presented along with their structural implications. The paper further highlights critical interface-related challenges such as waterproofing lapses, water-load effects, convergence zones, cross-junction transitions, clearance and tolerance management, mock-up validation, and the importance of proper debonding practices. Based on these observations, a set of practical precautions and engineering recommendations is proposed to ensure safer, more reliable, and higher-quality lining construction in NATM tunnels using gantries.

Keywords: *NATM Tunnel Lining; Tunnel Gantry Formwork; Concrete Workability; Crown Cavity; Honeycombing; Bulkhead Failure; Turnbuckle Prying Effect; Sway and Stability; Gantry Alignment; Plate Stiffness; Plate Deformation; Welding Defects; Kicker Beam Cracking; Kinematic Checks; Waterproofing Integrity; Water Load Effects; Construction Tolerances; Convergence Zones; Cross-Junction Detailing; Mock-Up Validation; Debonding Practices.*

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I. INTRODUCTION

Tunnels can be built in many ways, depending on the ground conditions, location, and purpose. Methods like Tunnel Boring Machines (TBM) create a tunnel in one go using large machines, while Cut-and-Cover involves digging a trench from the surface, building the tunnel inside it, and then covering it back. In areas with space constraints, Box Pushing - where pre-cast concrete boxes are jacked horizontally through the soil - offers a way to construct underpasses or shallow tunnels without major surface disruption. This also allows construction under live railway tracks with minimal disruption to traffic or services above.

But the New Austrian Tunnelling Method (NATM) works a bit differently. Instead of depending only on heavy machines or rigid designs, NATM makes use of the ground's natural strength. The tunnel is excavated in stages, usually starting from the top and then moving down in benches *(typically involves controlled blasting or mechanical excavation)*. Support is provided almost immediately after excavation. This method is often used in tunnels with changing shapes, softer ground, or where precise control is needed. That's where gantries come into picture, a special framework that helps with formwork, concrete placement, rebar arrangement and other support tasks inside the tunnel. Since tunnels built using NATM don't always follow uniform shapes or conditions, the use of gantries brings in a different level of challenge and opportunity.

In NATM tunnelling, especially when gantry systems are involved, success often lies in the details. Factors like how concrete behaves during placement, how vibrations are controlled, how well the gantry maintains its alignment, or how it adjusts through curves and varying tunnel profiles may seem routine, but they carry weight. These elements influence not just the pace of construction, but also the long-term safety and performance of the tunnel. With today's increasing expectations on quality and efficiency, a deeper understanding of these aspects becomes more than a good practice - it becomes a necessity.

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Fig 1- A Typ. TBM Machine

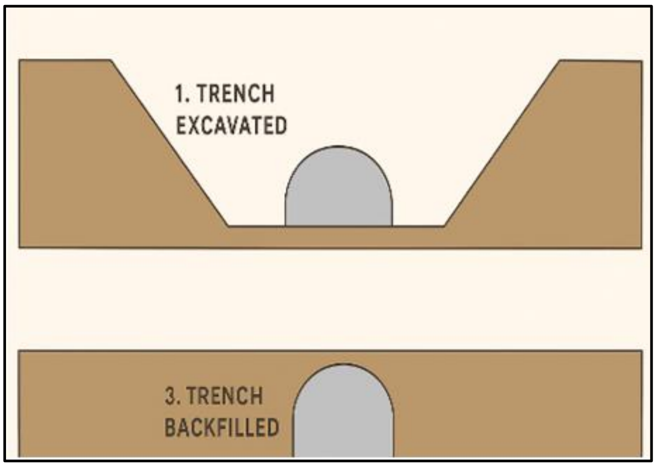

Fig 2 Cut & Cover Approach of Tunnelling


Fig 3 Typ. Box Pushing

II. GENERAL

An earlier published paper titled *"Tunnel Gantries: Fostering Safe, Efficient & Rapid Tunnel Construction"* offers a focused insight into how gantries improve overall tunnel construction, especially when working in difficult geological conditions or constrained environments. It highlights their contribution in ensuring speed by eliminating the need to manually erect and dismantle formwork for each segment. Once positioned, they can be quickly shifted to the next chainage using rails or wheels; alignment accuracy as gantry systems come with hydraulic and mechanical adjustments that allow fine-tuning in both vertical and horizontal directions; and safety by offering safe working platforms, ladders, and access points during in-situ concrete lining. While this current paper touches upon those basics, readers are encouraged to refer to that publication for a detailed foundation on tunnel gantry functions and system efficiencies before exploring the advanced aspects and precautions discussed here.


Fig 4 A Tunnel Lining Gantry Stationed at Hrishikesh-Karnprayag Rail Project Pkg 7b

➢ *Definition & Purpose*

In modern transportation infrastructure, tunnel gantries are 'fabricated structural steel frames' that are used to support formwork for tunnel lining and various equipment and machinery. Intermediate platforms are also provided in these gantries for workers to access and work on elevated or hard-to-reach areas.

➢ *Functional Roles*

Tunnel gantries serve multiple functions:

- Support panels for crown/roof, wall, and invert formwork.
- Facilitate concrete distribution from transit mixers to designated pour locations using buckets, skip hoists, or integrated concrete pumps.
- Allow movement in vertical and horizontal axes for alignment, levelling, and matching tunnel profile irregularities.
- Provide platforms, ladders, and walkways for safe worker access during reinforcement, inspection, and finishing activities.

➢ *Fabrication & Design*

Tunnel gantries are never off-the-shelf; they're custom-built to match the tunnel's profile, whether circular, horseshoe, or modified D-shape. Key design inputs include the pour length *(usually between 6 to 12 meters)*, final lining thickness, steel reinforcement layouts, and the total load the system needs to carry. This includes not just its own self-

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weight but also fresh concrete, labourers working onboard, and any equipment that needs to move with the gantry.

➢ *Movement and Handling*

Gantry movement is typically along pre-installed rail tracks or using heavy-duty rollers/sliders. It is manually controlled or power-driven with remote operation systems in modern setups.

III. ADVANCED ASPECTS & OPERATIONAL PRECAUTIONS IN NATM TUNNEL GANTRIES

Once the gantry is fabricated and positioned, its operation in the tunnel environment introduces a range of advanced challenges. Unlike typical formwork setups, tunnel gantries must perform its function reliably under restricted space, irregular tunnel geometries, dynamic alignment changes, and coordination with other machinery like transit mixers or shotcrete robots.

➢ *Gantry Alignment & Offset Control.*

Unlike mechanized tunnelling methods such as TBM, which produce a uniform circular profile throughout the drive, NATM relies on stage-wise excavation. This step-by-step process naturally introduces more variation in the tunnel shape. Two factors mainly contribute to this variability:

- Geological unpredictability and
- Human-driven construction tolerances.

In NATM, the tunnel design is intentionally flexible. The support system - shotcrete, bolts, ribs—must be adjusted according to how the ground responds at each chainage. As the excavation progresses, the surrounding soil or rock can deform, settle, or expand slightly due to stress relief. These responses may shift the actual tunnel profile away from the ideal shape. When the gantry moves forward into these zones, those uneven spots can prevent the formwork from sitting properly. This might cause the gantry to tilt slightly, lose its level, or shift off-centre, leading to misalignment during concreting.

The gantry is a rigid system, while the tunnel environment is dynamic and often unpredictable. The ground can shift, settle, or behave differently every few meters. This creates slight changes in the tunnel shape or level that the gantry doesn't automatically adapt to. That’s where offset control comes in—it helps adjust and fine-tune the gantry’s position so it continues to align with the actual tunnel profile, despite the natural movements and irregularities underground.

That's why regular checks and adjustments are essential to make sure the gantry continues to match the tunnel's evolving profile maintaining its required thickness of final lining.

Fig 5 Tunnel Stabilization in Progress

➢ *Managing Sway and Stability*

One of the main reasons gantries experience sway or instability in NATM tunnels is the condition of the base on which they move. Although the gantry runs on tracks or rails, the tunnel floor beneath these rails may not be always uniform. Soft patches in the ground, minor heaving, or gradual settlement caused by water ingress can create slight level differences along the base. When the gantry moves over these irregularities, or even when it is parked for pouring, it may lean, twist, or dip on one side. This tilt increases the likelihood of lateral sway during concrete placement, especially if the fresh concrete applies asymmetric pressure on the formwork. Even small deviations in level can affect the accuracy of the lining and the overall stability of the gantry, making frequent base inspections and re-levelling essential for safe operation.

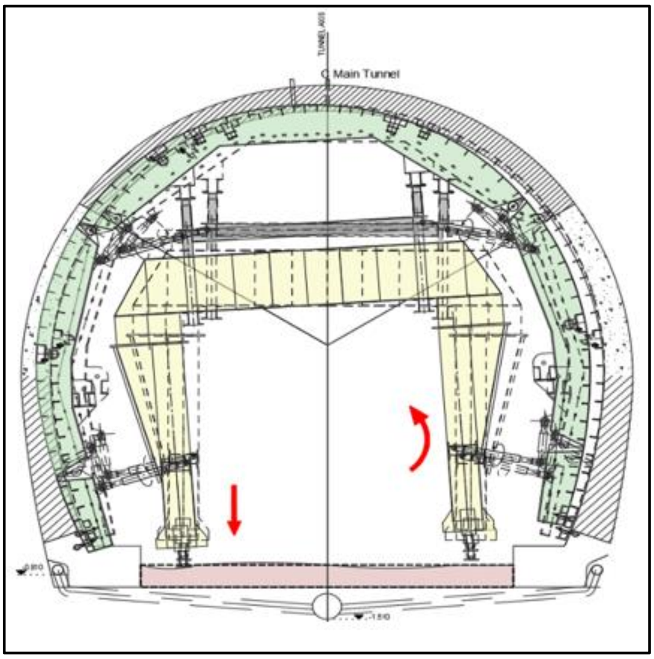

Fig 6 Illustration of Gantry Instability Under Uneven Base Conditions

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➢ *Concrete Placement Challenges in NATM Linings*

- *Effect of Limited Concrete Reach (Crown Cavity Formation)*

The crown is the most difficult location for concrete to reach in NATM tunnel lining because of its height, curved geometry, and restricted space behind the formwork. When concrete flow is interrupted or insufficient, voids—often called crown cavities—are formed. These cavities can develop due to:

✓ *Concrete not Reaching the Crown:*

Improper flowability, premature stiffening, long pumping distances, or blockages prevent the concrete from travelling fully to the top. As a result, the crown remains partially or completely unfilled.

✓ *Blockage in the Flow Path:*

Reinforcement congestion, misaligned formwork panels, or narrowed gaps restrict the upward movement of the mix. Even a temporary obstruction can cause a discontinuity in flow, leaving behind unfilled regions.

- *Effect of Improper Slump and Workability (Honeycombing Tendency)*

Concrete workability plays a decisive role in achieving a dense, void-free lining, especially in NATM where concrete must negotiate complex profiles and congested reinforcement. Improper slump can lead to honeycombing, a defect characterized by exposed aggregates and insufficient mortar filling. Consider if,

✓ *Slump is Too Low (Stiff Mix)*

The concrete lacks the mobility to flow around steel ribs, lattice girders, or tight formwork corners. Aggregates interlock before full compaction, leaving stone pockets that vibration cannot eliminate.

✓ *Slump too High (Overly Wet Mix)*

A very fluid mix increases segregation. Coarse aggregates settle prematurely, while the cement paste travels ahead, forming weak layers and small voids that later appear as honeycombed regions.

✓ *Loss of Workability During Pumping*

Long pump lines, temperature effects, or delays can stiffen the mix, reducing its ability to consolidate properly once placed inside the formwork.

Fig 7 Indicating Uneven (Stepping) Surface of Concrete Due to Panel Discontinuity

- *Precautions for Concrete Placement in NATM Linings*

To avoid crown cavities, honeycombing, and other concrete placement defects in NATM tunnel linings, the following precautions should be implemented:

✓ Keep concrete slump within the specified range (*typically 120–150 mm for tunnel linings*) to ensure adequate flowability without risking segregation. Recheck slump at the discharge end of the pump line.
✓ Avoid long pauses during concreting. Continuous flow minimizes cold joints, prevents stiffening in the pump line, and ensures the mix can travel fully to the crown.
✓ Ensure pump lines are clean, properly lubricated, and free from bends that may cause blockages or pressure losses. Position the discharge point to promote upward flow toward the crown.
✓ Use internal vibrators systematically along the walls and reach zones to eliminate air pockets and ensure uniform compaction. Avoid over-vibration to prevent segregation.
✓ Ensure the gantry is levelled and correctly aligned at each chainage. Misalignment can restrict concrete flow behind the formwork or create areas of reduced clearance that hinder upward movement.
✓ Ensure rebars, lattice girders, or utilities do not obstruct concrete flow. Minor relocations or spacing adjustments may be needed to maintain a clear flow path.
✓ Employ retarders or workability-retaining admixtures when long pumping distances or higher ambient temperatures risk premature stiffening inside the line.
✓ For critical crown sections or unusual profiles, conduct small-scale site trials to validate flow behaviour and adjust mix design or pouring sequence accordingly.

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- ✓ Have supervisors for monitoring the filling sequence, vibration pattern, and formwork response. Monitor concrete temperature to avoid rapid slump loss or setting.

➢ *Failure Of Bulk Head*

Bulk-head failure occurs when the end shutter or stopping panel is unable to resist the hydrostatic pressure of fresh concrete, causing concrete to leak or burst out from the end of the lining segment. This typically happens due to inadequate bracing, poor sealing at the edges, or misalignment between the gantry and tunnel profile. Rapid pumping and uneven support conditions can further increase pressure on the end panel, triggering deformation or complete blow-out. To prevent this, the bulk end must be properly sealed, tightly braced with the gantry body, and aligned, with controlled pouring rates and continuous monitoring of pressure during the pour. Pre-pour inspections and ensuring uniformity will greatly reduce the risk of such failures.

Fig 8 Bulk End Failure

➢ *Failure of Turnbuckle Plates in the Absence of Walers (Prying Effect & Undulation)*

In tunnel gantry systems, walers act as the primary horizontal stiffening members that connect to the runner plates of the gantry. Their purpose is to support and distribute the hydrostatic pressure of fresh concrete uniformly along the formwork surface before the load is transferred to the gantry frame. Turnbuckles, on the other hand, are intended only for alignment and fine adjustments of the formwork - not for resisting direct concrete pressure. When walers are omitted or inadequately installed, the fresh concrete load bypasses the stiff runner–waler system and is transferred differentially into the individual turnbuckles. This concentrates the pressure on the thin plates *(insufficient stifness)* connecting the turnbuckles to the runner plates, causing the plates to bend or deflect unevenly. In severe cases, the deformation can lead to bolt bending, plate tearing, or partial collapse of the formwork edge during the pour. Providing continuous walers, ensuring proper seating against the runner plates, and using turnbuckles purely for alignment are essential to prevent such differential loading failures.

Fig 9 Indicating Failure of Plate Due to Differential Settlement

➢ *Panel Discontinuity Leading to Poor Concrete Finish*

When the panels on either side of the formwork are not properly connected, concrete pressure is resisted by individual panels rather than the full continuous assembly. This causes uneven deflection, vibration, and rotation of each panel under pressure, producing steps, ridges, and misaligned surfaces in the final lining. These discontinuities also create pathways for paste leakage, resulting in honeycombing and weak surface zones. Proper panel interlocking ensures uniform stiffness across the side and maintains the required profile during concrete placement. Gaps between these panels also allow paste leakage, leading to surface blemishes, honeycombing, or inconsistent texture.

- *Other Reasons Could Be:*

- ✓ Inadequate Bracing or Waler Continuity *(Stiffening)*.
- ✓ Misaligned Runner Plates or Gantry Frame Distortion
- ✓ Local Buckling of Skin Plates after multiple cycles of pouring.
- ✓ Poor Vibration Technique Leading to Segregation at Panel Joints

➢ *Failure Due to Inadequate Skin Plate Thickness & Stiffener Spacing*

If the skin plate of the gantry formwork is too thin for the concrete pressure it is designed to resist, it can deform locally during pouring. Fresh concrete applies uniform lateral pressure on the formwork surface, and thin plates flex more easily, causing bulging, rippling, or inward dents. This also leads to an uneven concrete finish, variations in lining thickness, and in severe cases, local buckling or permanent distortion of the formwork panel. Differential vibration from compaction further amplifies this deformation, especially in wide unsupported zones between stiffeners. Ensuring adequate plate thickness, combined with proper stiffener spacing and regular inspection for fatigue-related thinning, is essential to prevent such failures.

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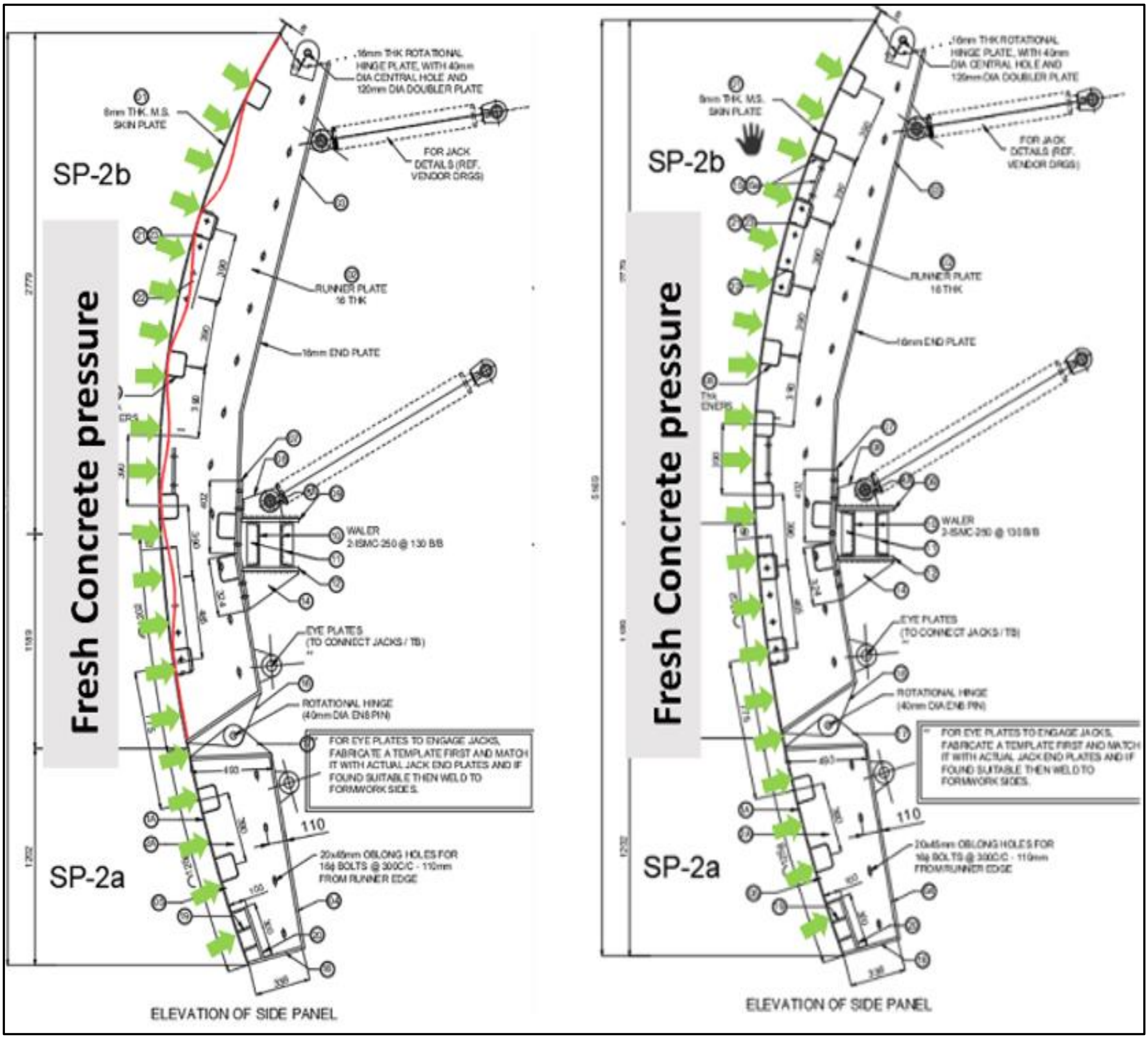

Fig 10 Bending of Skin Plate (Highlighted in Red, Left)

➢ *Failure Due to Improper Welding of Gantry Formwork Components*

Welded joints are one of the most critical elements in a tunnel gantry because almost every load path—from skin plates to runner plates, walers, brackets, stiffeners, and jack seats—depends on weld integrity. If the welding is inadequate, mismatched, or not executed as per fabrication drawings, the gantry becomes vulnerable to several structural failures. Poor welds can develop cracks under repeated loading, detach under concrete pressure, or fail suddenly when the gantry is being shifted. Even minor weld defects such as lack of fusion, porosity, undercut, or improper throat thickness can compromise the stiffness of the formwork assembly and lead to uncontrolled deflection or panel misalignment during pouring. In severe cases, weld failure can cause partial detachment of runners or stiffeners, resulting in leakage, blow-outs, or unsafe movement of the gantry.

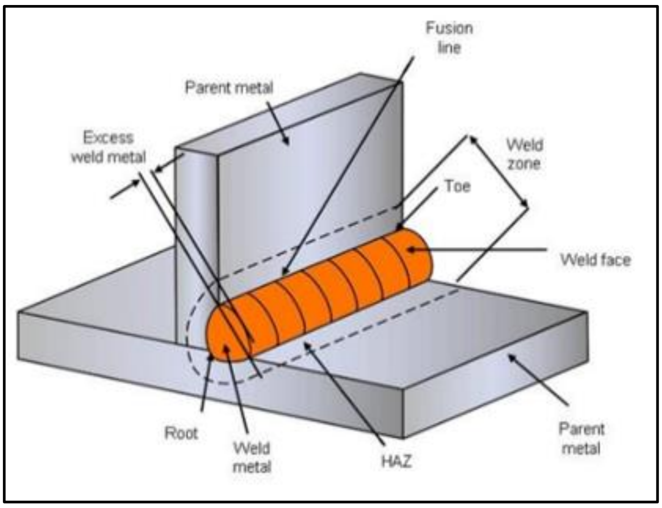

Fig 11 Typ. Weld Details

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Fig 12 Highlighting Initial Cracks Observed in Kicker Beam (Top) & Spalling of Concrete After Removal of Pins (Bottom)

In India, welding for structural elements such as tunnel gantry components must comply with the requirements laid out in relevant Indian Standards. The selection of welding process—whether SMAW (MMAW), GMAW (MIG/MAG), or FCAW—must align with IS 9595 (Welding and Welders' Qualification) and IS 816 / IS 814 for the use of electrodes and welding practice for mild- and low-alloy steels. The filler or electrode material (commonly E6013 or E7018 class for structural applications) should match the parent steel grade as per IS 2062 (structural steel specification) and meet the weld size, throat thickness, and detailing shown on the approved fabrication drawings. Welds must also undergo quality checks according to IS 822 (Code of Practice for Inspection of Welds) and, where necessary, non-destructive testing such as Dye Penetrant Testing (as per IS 3658) or Ultrasonic Testing (as per IS 12666) to ensure proper fusion and detect hidden defects. Only certified welders qualified under IS 7310 or IS 817 should be allowed to perform structural welds. Adherence to these standards ensures that all weld joints remain structurally sound during repeated pour cycles, vibration, gantry movement, and the significant lateral pressures generated during tunnel lining operations.

All these welding requirements must be strictly implemented and verified at the fabrication site itself, before the gantry is transported to the project location. The fabrication yard is the controlled environment where correct weld procedures, material selection, welder qualification, and dimensional accuracy can be ensured without field constraints.

➢ *Cracking of Kerbs (Kicker Beam) Due to Lateral Pressure.*

The kicker beam (the small concrete starter block cast at the base of the formwork) provides the seating, alignment, and lateral restraint for wall shutters during tunnel lining. It is not designed to resist high horizontal loads, especially during the early-age green concrete stage. When excessive lateral forces are transferred to this kicker, cracking, spalling, or shear failure can occur even before the permanent lining gains adequate strength.

Adequate early-age strength of the kicker should be achieved by allowing sufficient curing time or by using an early-strength mix when rapid cycles are required. The invert surface must be properly levelled and compacted before casting the kicker to avoid differential settlement and shear cracking. Additionally, vibration near the kicker should be minimized, and starter bars must be anchored as per drawings to ensure that the kicker behaves compositely with the invert. These precautions collectively ensure that the kicker beam remains stable and intact during formwork erection and concreting.

➢ *Failure Due to Improper Kinematic Checks of the Gantry*

Kinematic verification ensures that every moving part of the tunnel gantry—rollers, hinges, hydraulic legs, telescopic arms, slewing joints, and formwork articulation—moves exactly as intended throughout the full range of motion. If this kinematics are not checked at the initial setup stage, the gantry may bind, jam, or move non-uniformly when shifted forward or when the formwork is opened and closed. Misalignment between moving members creates uneven loading on rollers and jacks, causing sudden jerks, frame distortion, and unintended lateral forces being transferred into the kicker beam or side shutters. In more severe cases, lack of kinematic clearance can lead to rubbing of panels against excavation surfaces, collision with reinforcement, or overstressing of hydraulic cylinders. Performing a full kinematic review—checking clearances, synchronisation of hydraulic legs, free movement of hinges, and smooth travel of the gantry—before any concreting cycle ensures safe operation and prevents structural or mechanical failures during movement.

IV. CONSTRUCTION INTERFACE CHALLENGES AND PRE-POUR PREPARATION REQUIREMENTS

Before final lining operations begin, several site-specific and interface-related conditions must be verified to ensure that the gantry, temporary support, waterproofing

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system, and surrounding ground all work as intended. Unlike equipment-related failures, these issues arise from construction tolerances, geometric mismatches, incomplete preparatory work, or overlooked coordination between successive excavation and support stages. If not addressed in advance, they can lead to water pressure build-up, misalignment of the formwork, obstruction during gantry movement, or defects at junctions between different tunnel sections. The following subsections outline the major interface challenges and the corresponding precautions.

Fig 13 Typ. Overstressed Rock Mass

- *Effect of Water Load During Construction of Lining*

During NATM tunnel lining, the permanent concrete is not designed to withstand direct hydrostatic water pressure in its fresh or early-age state. This is why a waterproofing membrane - either full-round or umbrella-type - is installed between the temporary support *(shotcrete)* and the final lining. If this waterproofing is not provided, or is damaged or incomplete, groundwater or seepage can accumulate behind the formwork and apply unintended water load on the green concrete. Even a small head of water at this stage can cause outward bulging of the lining, micro-cracking, loss of cover, or washout of cement paste near the extrados. Water trapped in the annular gap also prevents proper bonding between temporary support and final lining, creating long-term seepage paths and local delamination. In extreme cases, inflow during the pour increases pressure on the formwork and gantry, raising the risk of leakage or blow-out.

- *Effects of Converging Zones*

In NATM tunnels, certain sections experience higher deformation known as convergence zones, where the surrounding ground continues to move inward even after initial support installation. These zones are typically associated with weak strata, high overburden, or delayed shotcrete strength gain. If the gantry is moved into such areas without prior identification, the narrowed profile can obstruct its travel path, cause panels to scrape against the temporary lining, or induce tilting and unexpected lateral forces on the jacks and rails. Therefore, convergence behaviour must be monitored through convergence pins, total station readings, or laser scanning so that the exact clearance between the temporary support and the formwork envelope is known.

Additionally, construction tolerances—including actual tunnel diameter, offsets from design profile, invert levels, and available clearance at crown - must be verified well in advance of gantry movement. Even small deviations can prevent the formwork from seating properly, restrict opening/closing of panel wings, or cause binding of the gantry during longitudinal movement. Mapping these tolerances beforehand ensures that adjustments, trimming, or minor shotcrete corrections can be executed before the gantry reaches the location, preventing delays, misalignment, and potential damage to the formwork.

- *Moving Forward Bonding & Debonding of the Gantry Before Moving Forward*

During NATM lining operations, gantry formwork often comes into close contact with the fresh concrete, especially at the kicker, side shutters, and crown interfaces. If proper separation measures are not in place, portions of the gantry - such as skin plates, runners, end shutters, or alignment plates - may accidentally bond with the hardening concrete. Even a thin paste layer can lock the gantry to the lining, making forward movement difficult and causing jerks, twisting, or bending of members when force is applied to disengage it. In severe cases, excessive pulling force can damage the newly cast lining, distort the formwork, or misalign the gantry for the next cycle.

To prevent this, debonding must be ensured at every pour, using approved release agents, polyethylene sheets, or designated separation strips at contact regions. All interfaces—especially at kickers, panel edges, crown overlaps, and bulkheads—should be checked before pouring to confirm that no steel part of the gantry is inadvertently touching reinforcement or concrete. After the pour, but before movement, the gantry should be carefully inspected to confirm that no residual concrete nodules, laitance, or paste buildup has created mechanical locking. Controlled loosening of jacks, cleaning of bearing edges, and releasing the formwork in a predefined sequence ensure smooth detachment and prevent structural or mechanical damage during advancement of the gantry. Also, when debonding agents such as oils or chemical release compounds are applied to prevent the gantry formwork from sticking to the fresh concrete, it is essential to ensure that these materials do not come into contact with the reinforcement. Any accidental spraying or misting on the rebar can create a thin oily film that significantly reduces the bond strength between steel and concrete, leading to slip, reduced anchorage capacity, and potential long-term durability issues and may compromise crack control in the lining. Therefore, debonding agents must be applied only on the formwork surfaces, using controlled, low-pressure spraying or with the help of rollers.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25dec486

➢ *Precautions at Junctions & Cross Passages*

When the tunnel transitions between MT, DT, TT the lining profile changes significantly, requiring the gantry to be reconfigured with different panel sets. These transitions often involve widening, narrowing, or shifting of the tunnel cross-section, meaning the standard panel arrangement used in the previous chainages will no longer fit the new geometry. In the confined environment of a NATM tunnel, replacing crown panels, adjusting side shutters or installing customised end shutters become challenging due to limited manoeuvring space and restricted visibility. Proper arrangements shall be done according to the site & constructability requirements.

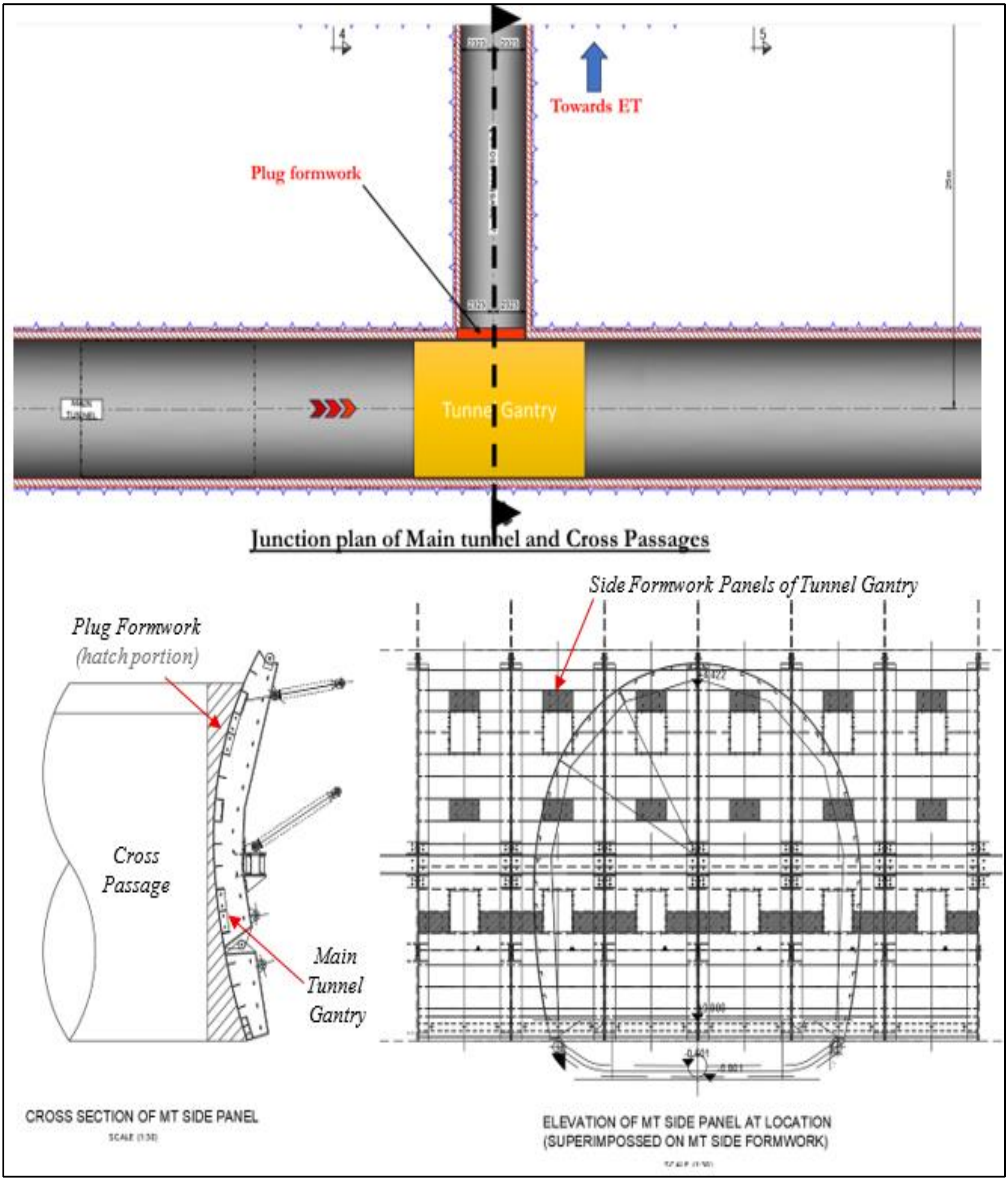

Fig 14 Highlighting Details of Plug Formwork at Cross Passage

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Fig 15 A Typ. Cross Passage Plug Formwork Fabricated by Rubrica Engineering

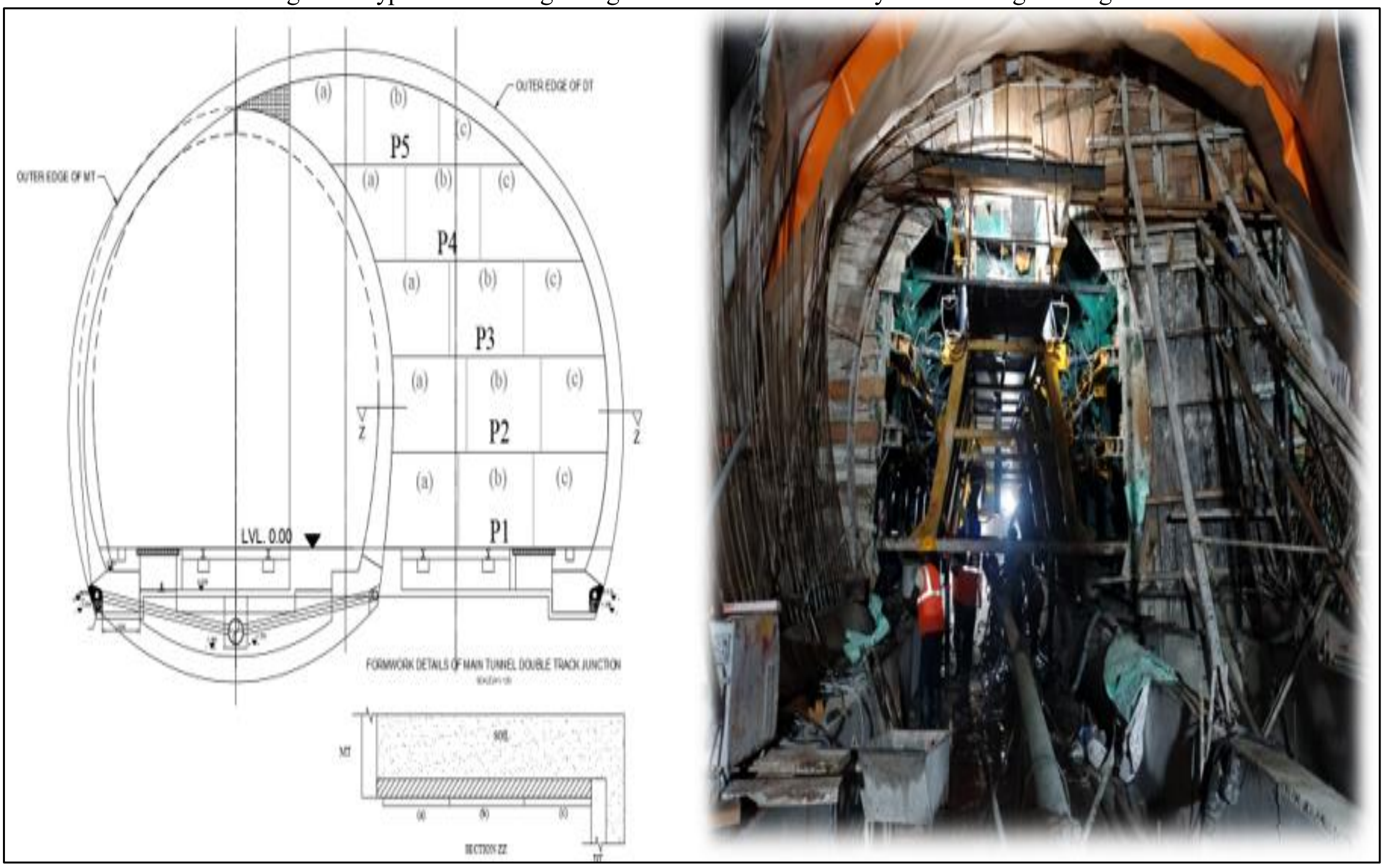

Fig 16 Typical Junction Formwork at MT Tunnel Transitioning from Double Track Tunnel

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Cross passages introduce another complexity: the lining often requires a step, recess, or niche to accommodate the opening. Special customised end shutters, curved bulkheads, or stepped panels must be prepared beforehand rather than improvising on site. Generally called as Plug formwork. Waterproofing laps in these zones are particularly vulnerable—sharp curvature changes can tear membranes if the gantry presses against them. Hence, manual guiding, slow advancement, and a pre-check of waterproofing clearances are essential before positioning these formworks.

- *Clearance Shall be Taken in Account Before the Fabricated Parts are Transported to Site.*

Before tunnel gantry components are transported to site, it is essential to verify that sufficient clearance exists inside the tunnel for all equipment that will operate alongside the gantry-such as transit mixers, pump lines, shotcrete robots, ventilation ducts, service vehicles, and temporary utility lines. NATM tunnels often have irregular profiles, ongoing convergence, and temporary supports placed at varying offsets; without proper clearance assessment, the fabricated gantry panels, runners, or hydraulic jacks may clash with lattice girders, waterproofing membranes, or other in-tunnel machinery during installation or movement. Based on this, adjustments to panel widths, runner spacing, hydraulic leg positions, and folding mechanisms can be planned well in advance.

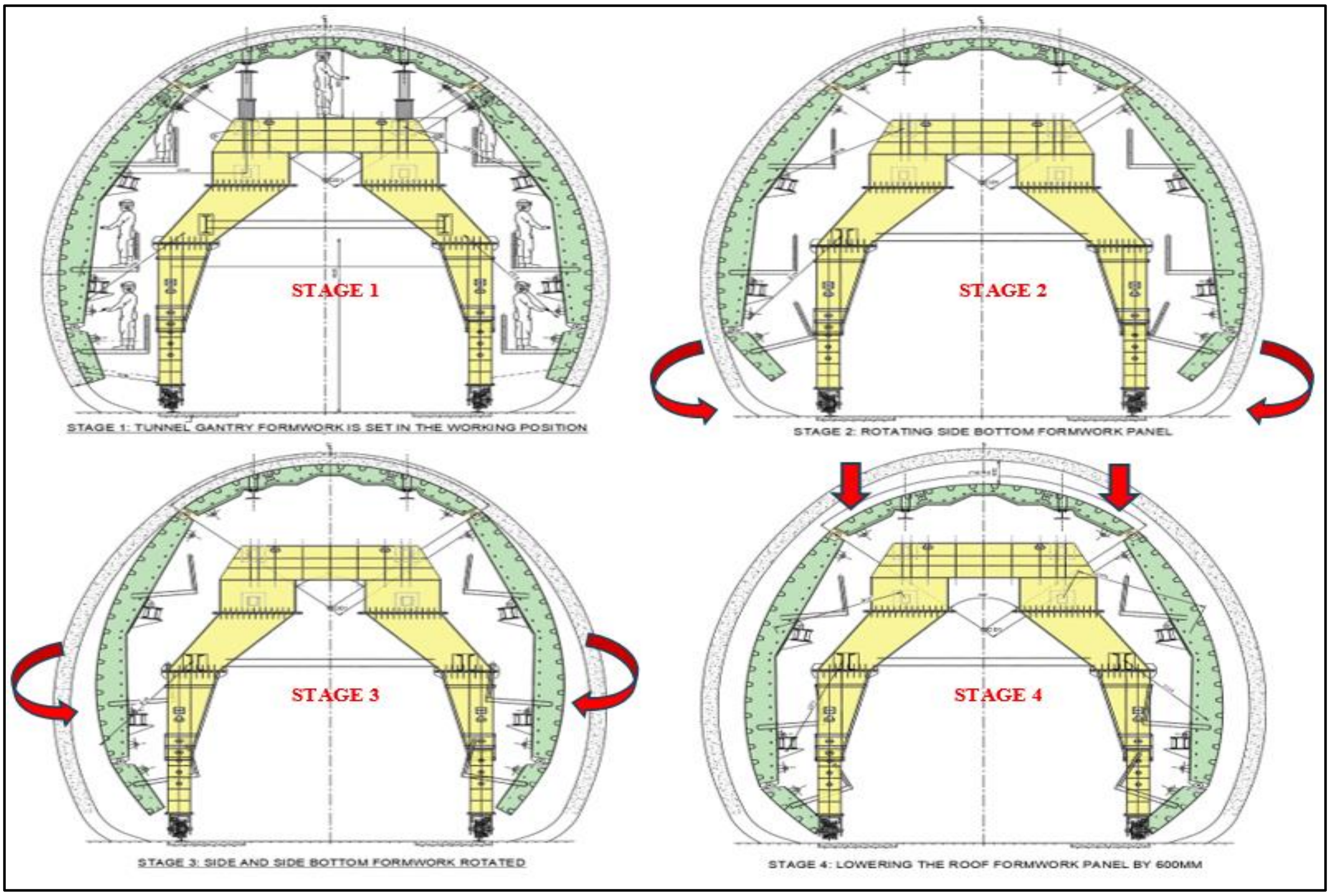

Fig 17 Kinematic Sequencing of Tunnel Gantry

Because actual conditions inside NATM tunnels often differ from the ideal design profile, carrying out mock-up drills at the fabrication yard becomes an essential step before the gantry is transported to site. These drills allow the entire gantry to be assembled and its kinematics thoroughly tested—checking articulation of panels, the opening and closing sequence of shutters, the movement of telescopic and hydraulic legs, and the behaviour of hinges, runners, and jacking points throughout their full operating range. By simulating equipment passage and gantry shifting in a controlled environment, the team can detect misfits, clashes, inadequate folding space, or areas where hydraulic or mechanical travel is restricted. This early-stage verification of kinematic sequencing ensures that all motions occur smoothly, synchronously, and without binding, which is critical for safe operation in the confined tunnel environment. Any design adjustments, reinforcement additions, or dimensional corrections can be implemented easily at the yard—long before the gantry enters the tunnel—thus preventing costly delays, unsafe improvisation, and potential damage to both formwork and tunnel support systems. Properly executed mock-ups ensure that once deployed, the gantry can be installed, operated, and advanced confidently without obstruction or unexpected mechanical constraints.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25dec486

➢ *Swaying of Gantry Due to Differential Pouring Sequence*

During tunnel lining, the concrete in the left and right wall sections must rise uniformly to avoid creating an unbalanced lateral load on the gantry formwork. It is critical to maintain a maximum height difference of 500 mm between the two sides at any point during the pour. Exceeding this limit causes a differential hydrostatic pressure that pushes the formwork unevenly, resulting in lateral sway, panel misalignment, or tilting of the entire gantry assembly. Since gantries are tall, slender structures with multiple articulated points, even a small imbalance in pressure can magnify into noticeable movement at the crown level. This not only compromises the accuracy of the lining thickness but also increases stress on hydraulic jacks, runners, and anchor support.

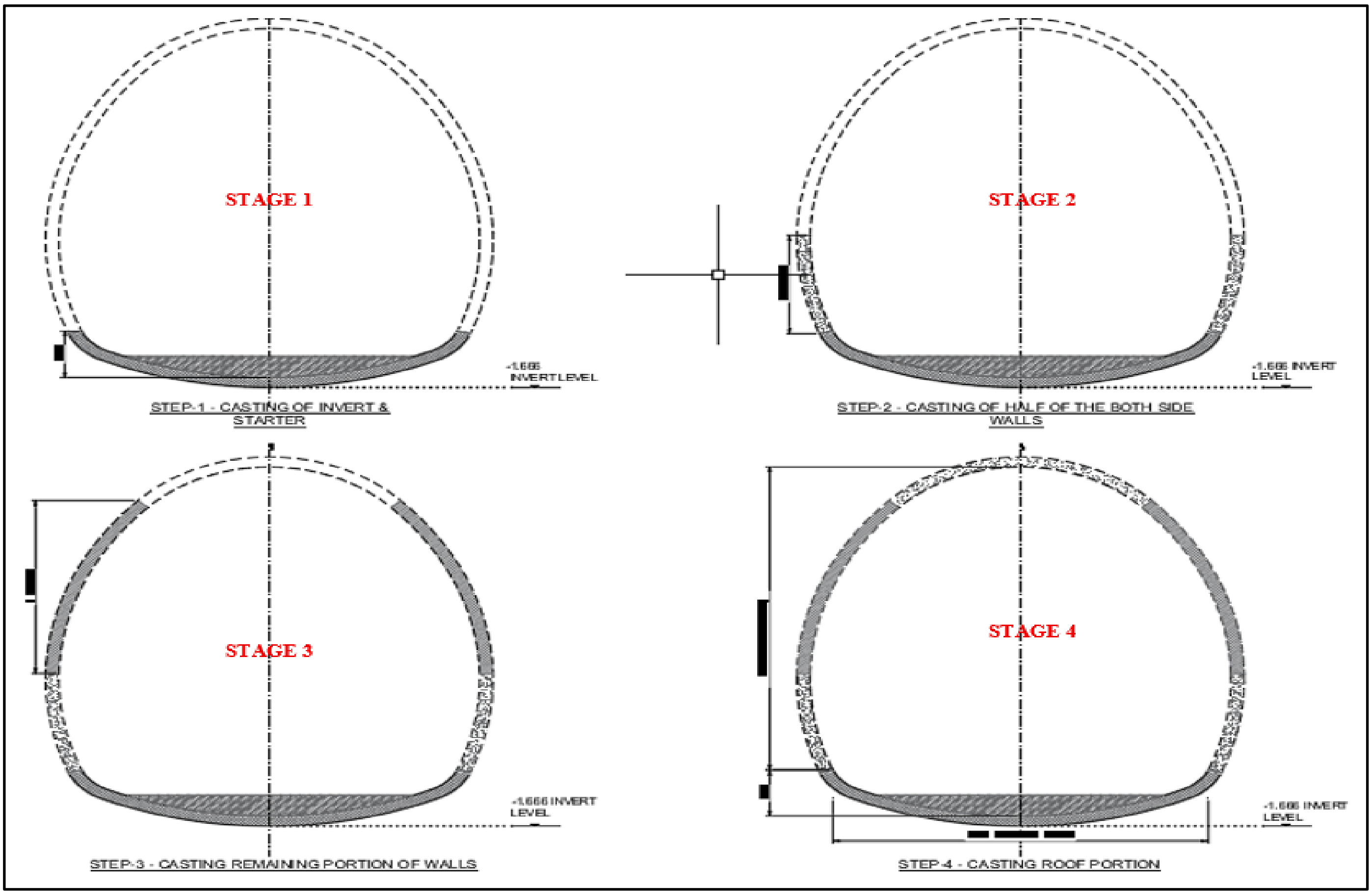

Fig 18 Concrete Pouring Sequence

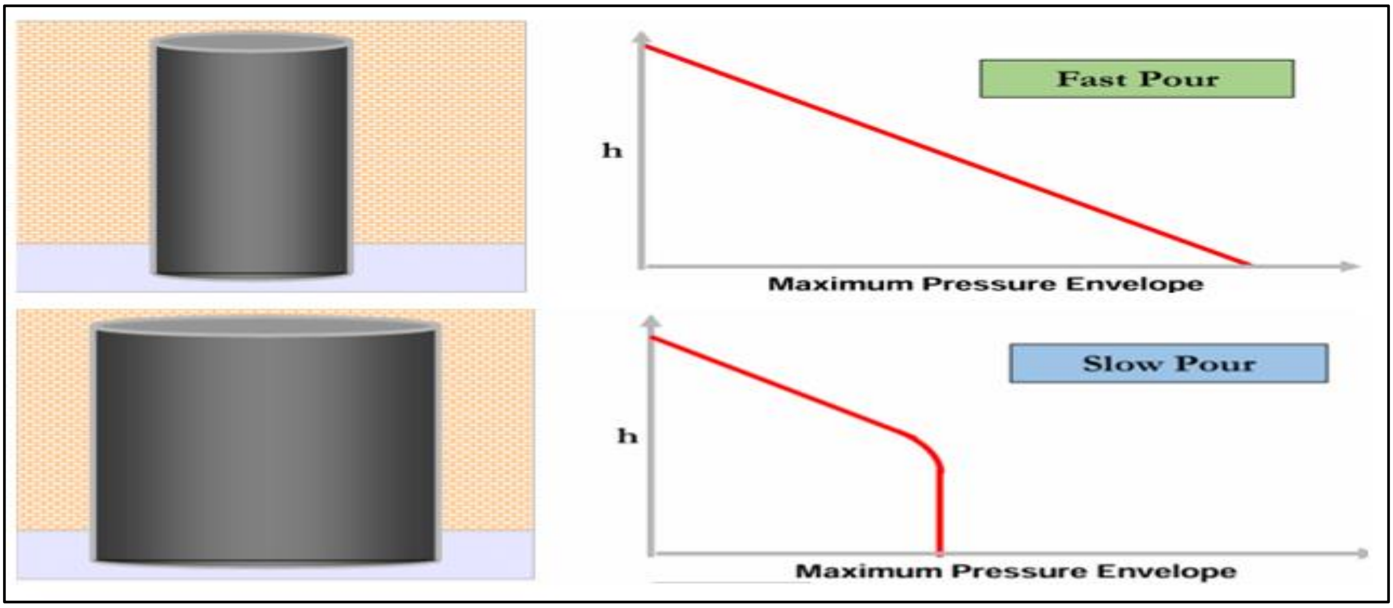

Fig 19 Concrete Pressure Envelope

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The concrete pouring rate directly affects this behaviour. Faster pouring on one side or delays in pump switching can create sudden load differences that the gantry may not be designed to resist. Hence, the pour sequence must be carefully controlled and coordinated: concrete should be alternated between sides at regular intervals, with constant monitoring of level markers to ensure synchronicity. The gantry's design—especially its lateral stiffness, jack spacing, and anchorage—assumes that this level difference will be kept within acceptable limits. Any deviation increases the risk of sway, misalignment, or overstressing of the formwork components. Maintaining balanced pour rates and adhering strictly to the allowed height difference is therefore essential for both the stability of the gantry and the quality of the tunnel lining.

V. CONCLUDING REMARKS

Construction of final tunnel linings in NATM involves more than simply positioning a gantry and placing concrete. The method's inherent variability-arising from sequential excavation, changing ground responses, irregular profiles, and continuous adjustments to temporary support-demands a high degree of technical discipline in how gantry systems are designed, assembled, aligned, and operated. This paper has highlighted that even small deviations in alignment, offset, slump control, vibration, or base conditions can propagate into larger structural and operational issues, affecting both safety and quality.

The practical observation emphasises that the gantry must not be viewed merely as a formwork frame, but as a dynamic, precision-controlled mechanism that interacts closely with excavation geometry, concrete behaviour, waterproofing layers, and in-tunnel equipment constraints. Failures such as bulkhead blow-outs, crown cavities, honeycombing, prying-induced plate deformation, welding defects, and kicker beam cracking are rarely the result of a single mistake; they occur when multiple process lapses converge-often during the same pour. Proper kinematic sequencing, balanced pouring rates, continuous base monitoring, and careful reconfiguration of panels in transition zones (MT–DT–TT and cross passages) are therefore essential to maintaining alignment and structural reliability.

Equally important are the construction interface requirements. Waterproofing integrity, convergence mapping, tolerance verification, clearance studies, and fabrication-yard mock-up drills form the backbone of prevention before any mishaps. These measures ensure that the gantry can be installed, adjusted, and advanced without obstruction or unanticipated loading, thereby reducing rework and safeguarding the final lining.

Overall, the insights presented here reinforce a simple truth: NATM gantry operations succeed when precision, planning, and process control work together. As tunnel projects in India and elsewhere grow more complex-with tighter timelines, varied geological settings, and higher quality expectations. By integrating the precautions and engineering practices discussed in this paper, construction teams can achieve safer operations, better concrete performance, and long-lasting tunnel linings that perform as intended throughout their service life.

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