Utility Tunnelling – Longer, Deeper, More Curvaceous

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Utility Tunnelling, comprising both pipe jacking and microtunnelling, develops into the prevailing construction method at global level for drains and sewers in metropolises. This popularity growth is accompanied by the need for ever-more demanding projects. To put it simply, utility tunnelling projects take on increasing depths and lengths. Examples are, inter alia, projects which are also called “Deep Tunnel Sewerage System” or the “Deep Gravity Tunnel” in Singapore (PUP) and Germany (Emscher Genossenschaft), where huge sewage collectors (DN/ID 1400 to 2800) are installed entirely trenchlessly over distances of 50 km and more. In addition, there is a demand for the installation of curves, S-curves and several space curves within a section to optimise line alignment and improve economic competitiveness.

However welcome this development is, it is alarming to see how little the valid standards of different countries used for structural calculation and design meet the complexity of civil engineering structures. Despite the enormous investment costs, the instruments for quality assurance that are now widely available are only rarely used to a sufficient extent.

The subsequent content is about critical influencing factors that are normally not considered in the design of such structures. Proposals for solution and concepts for quality assurance are offered that can be used in the planning stage and construction phase. Both clients and building contractors benefit greatly from those proposals and concepts in terms of safety, efficiency and quality.

1.1 Where are the sources of error and safety hazards in designing jacking pipes

The installation method of utility tunnelling has made tremendous progress over the last 30 years. Jacking spans with lengths of more than 1,000 m and s-curves are quite common these days. The international standards and regulations for the design of jacking pipes used in utility tunnelling are nowhere near to keeping pace with this development. The calculation approaches valid to this day that do not consider unavoidable steering movements and (permissible) production tolerances for jacking pipes as well as the calculative approach of a constant E-modulus for the pressure transfer ring reach their limits, at the latest, in the demanding utility tunnelling projects mentioned earlier. This evaluation is no theoretical assumption, but is based on extensive expert reports on damages Prof. Dr.-Ing. Stein & Partner GmbH and the affiliated company S & P Consult GmbH were involved in as experts. The lack of knowledge on the actual stresses of the jacking pipe due to jacking forces and angular deflections in the joints caused a lot of damage. Although the revised version of the DWA (German Association for Water, Wastewater and Waste e.V) worksheet that will presumably be published in the course of 2011 will generally consider the most important influencing factors (steering movements, production tolerances, pre-loading of the pressure transfer ring), it cannot cover individual jacking situations with sufficient accuracy.
According to the latest state of the technology and in the absence of an appropriate calculation method, a constant modulus of elasticity is used for the pressure transfer ring in the structural verification process of planning a jacking measure. Due to the inevitable lack of precision this constant has to be chosen on the safe side. Thus, the structural calculation of the jacking pipes can only be a “snapshot” of jacking, in which only one specific angular deflection of the pipes, one jacking force, and also only one stiffness of the pressure transfer ring are included in the calculation in the form of the E-modulus. The time- and load-dependent, highly non-linear material behaviour of the pressure transfer ring made of wood or wooden materials is completely ignored (Figure 1). As a general rule, a second check of the load assumptions and changes of the pressure transfer ring during jacking made in structural calculations remains undone. Consequently, the actual stress of the jacking pipes and the current level of safety remain completely unknown.

The results are jacking sections limited in length that needlessly make the construction measure more expensive, smaller permissible jacking forces with the consequence of a longer construction time, or an increased risk regarding overstress of the pipes during jacking. Despite the continuous acquisition and recording of the most important jacking parameters specified in the standards and regulations, a construction-accompanying update of the structural calculation inclusive of an adjustment of the permissible jacking force (increasing or decreasing) considering the specific characteristics of the pressure transfer ring has not been done so far.

Another discrepancy can be found between the planned and installed line. From a planner’s point of view there are only the straight line and the circular arc. The machine operator has to translate these into reality considering the steerability of the microtunnelling machine and a pipe string that represents a chain. Depending on the competence of the machine operator, the type and composition of the subsoil, and the measuring and steering technique, this works more or less effectively. On no account does the installed line meet the planned and ideal line elements straight line and curve. The inevitable clothoidal transition curves alone, resulting from a change in the line curvature, create a deviation from the nominal axis that has to be counterbalanced by additional steering movements. To put it simply, too many and/or too large steering movements rapidly lead to unplanned and significant increases of the jacking force and, in the worst case, so large angular deflections between the pipes that overstress of and damages to the jacking pipes can no longer be excluded.

1.2 A chain is no stronger than its weakest link

“A chain is no stronger than its weakest link” – if we apply this well-known saying to the chain “pipe string”, the weakest link would be the pipe joint. The central structural issue in pipe jacking is the transmission of jacking forces from pipe to pipe. With pipes made of reinforced concrete or
vitrified clay, in particular, the pipe string does not bend continuously in curved jackings and in steering movements, but the “stiff” pipe remains largely straight. This results in angular deflections in the pipe joints which are recognisable in the form of different joint gap widths all over the circumference of the pipe joint. If the deflection is big enough, a gaping joint is formed (Figure 2) that reduces the pressure transmission surface, resulting in an inevitable increase of contact pressure.

The pressure transfer ring (PTR) moderates this effect (Figure 2). It reduces stress, because it can deform due to the lower stiffness of wood or wooden materials. Thus, it increases the contact area available for pressure transmission at the pipe faces [2, 3, 4, 5, 6].

The bigger the forces and the number and extent of the steering movements, the more the pressure transfer ring is loaded far beyond its limit of elasticity. This load results in irreversible plastic compressions that persist even after the pressure transfer ring is unloaded (Figure 1). Each pressure transfer ring is loaded and unloaded many times during a jacking measure. Furthermore, the angular deflection changes constantly. Thus, the pressure transfer ring changes its geometry and increasingly loses its load-distributing effect, it “hardens”.

Damas to the exterior pipe are particularly frequent, because normally, the stress is highest there. The concrete cover of the reinforcement, in particular, cannot withstand the high contact pressure and flakes off. Often this typical damage is not visible from the inside of the pipes, but is such a substantial adverse effect on the durability of the whole construction that even more severe consequential damages and a considerable need for rehabilitation must be expected after a few years before or after the warranty period expires (Figure 3). In this example not only the serviceability (reliability of the seal) is impaired, but also the stability (corrosion of the load-bearing reinforcement).
1.3 State of the technology in calculating pipe stress

A more accurate structural calculation of the pipe stress considering the non-linear stiffness behaviour of the pressure transfer ring is absolutely necessary to ensure a sufficiently high level of safety. The economic practicability must also be taken into account. Essential input parameters for a calculation of the pipe stresses from the engineering viewpoint are:

- Non-linear stiffness behaviour of the pressure transfer ring, separating the elastic and plastic deformation portion,
- Stress history of the pressure transfer ring at any point in time under observation,
- Changes in the stiffness and geometry of the pressure transfer ring in the course of jacking,
- Temporal development of the longitudinal force and
- Chronology of the traversed line geometry.

The list clearly indicates that the calculation of pipe stresses must not be limited to a single point in time, but requires a consideration of the above mentioned parameters during the construction phase.

First scientific approaches of a construction-accompanying update of the calculated assumptions by means of measurement data from the construction site based on the Finite Element Method are documented in [5]. Comprehensive investigations followed regarding the actual stress and compression behaviour of pressure transfer rings and the evaluation of damages which occurred in jacking measures. S&P Consult GmbH, in particular, investigated the mathematical formulation of the theoretical assumptions for calculation and developed an entirely new calculation method which not only determines the actual stress conditions during jacking accurately, but allows for a...
forecast for the remaining distance still to be traversed. By now, a field-proven controlling system called CoJack has been created that can be installed without any problems at a reasonable price. It allows both building contractors and clients a web-based online check of the pipe stresses on the Internet in close to real time [2, 7].

1.4 CoJack - The structural controlling system in practice

1.4.1 What does CoJack do?

With the structural controlling system called CoJack, developed by S&P Consult GmbH, Bochum, Germany, a practical and powerful instrument for increasing the safety and economy of pipe jacking methods is now available. Among others, it takes into account the following input parameters listed in paragraph 1.3 that have a great influence on pipe stress, but which have been ignored in the previous methods of calculation.

In 2004, using this program, it was possible for the first time to determine and show the ever-changing stresses of pipes during jacking via a structural simulation. The stress conditions of the reinforced concrete pipes are determined at the end faces at any time of jacking, depending on the load history of the pressure transfer ring. A forecast that is always up-to-date is also calculated for the pipe stresses of the upcoming jacking distance. All essential input parameters are taken into account, as e.g. the non-linear stiffness behaviour of the pressure transfer ring that is known to significantly change to the unsafe side under the ever-changing load during jacking (load history) [7]. Based on this, CoJack particularly allows:

- The determination of the pipe stress as a result of loading in the direction of the pipe axis
  - For each pipe
  - For each point in time under observation during jacking
- The safe use of increased jacking forces, if necessary
- The safe continuation of jacking after steering errors and an exceedance of the jacking force
- The consideration and evaluation of scenarios regarding the development of the jacking force and to high steering movements on the remaining jacking still to be installed (remaining distance)
- A complete, comprehensive and, in particular, comprehensible documentation of jacking
- Permanent and location-independent observation of jacking data, displayed graphically on the Internet (corresponding access rights presumed)

The great interest in the increase of controllability, and consequently also the safety of demanding jacking measures, especially on the part of the clients, but also on the part of the building contractors, led to an increased demand for this service in Germany and abroad. Thus, essential practical experience could be gained that facilitate a practical further development and optimisation of CoJack.
By now, CoJack is used in all three essential phases of jacking measures: **planning, construction supervision** and **approval**.

In the planning stage a pre-simulation of jacking is created with the planning data based on the structural analysis of the pipe manufacturer. In the process the structural calculation of the pipes at hand is checked, verified, and its scope is defined. This approach is essential, because standard structural calculations according to ATV-A 161 [8] are known to be limited to the calculation and specification of **only one single permissible jacking force in the form of a fixed value for the entire jacking measure**. Normally, no statements are made regarding the development of the permissible jacking force and permissible steering movements in particular. CoJack provides these missing structural specifications that are essential for the execution of the construction measure. On the basis of the expected jacking force (red line in Figure 4), not only the usual single fixed value is defined for the permissible jacking force (blue line), but a linear limiting curve is given (green line), that should not be exceeded during jacking.

![Graph](image_url)

Figure 4: Development of the jacking force – Illustration of planning data and data measured at the construction site (blue line: fixed value for permissible jacking force according to standards, red line: expected jacking force, green line: limiting curve based on CoJack, black line: real data from construction)

Analogously, the planned curvature of jacking (red line in Figure 5) is superimposed by the expected steering movements (blue line). This results in a range for permissible curvatures of the pipe string as limiting values for the execution.

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As a general rule, the simulation of the upcoming jacking reveals that the permissible jacking force stated in the structural calculation of the pipes can continue to apply unalteredly. But now corresponding limits for the extent and frequency of steering movements can also be indicated. Thus, the conditions are defined under which the permissible jacking force applies. To allow for practical steering movements, the permissible jacking force stated in the structural calculation of the pipes has to be slightly decreased only in exceptional cases.

But the main field of application for CoJack is the simulation and control of the pipe stresses during construction. For this purpose special sensors recording the required measurement data are installed at the construction site (Figure 6). These data are transmitted via Internet to the server of S&P in real time (see Paragraph 1.4.2). The curves of measured values and the corresponding limits are prepared and graphically displayed on the Internet. This modern transmission technology allows for a prompt structural resimulation of jacking.

Normally, the limiting values defined in planning are kept, so that CoJack simply offers an additional means of control and documentation. Thus, it serves a structural validation in particular.

From time to time there are unexpected incidents during jacking that have not been considered in planning. Without CoJack, these are often recognised too late. Consequently, they can lead to damages to the pipes, a longer down time or the termination of jacking.

1.4.2 Measured data replace planning data

In accompanying the ongoing jacking CoJack relies on precise and up-to-date measured values at site. For this purpose partner companies (ILM, Stolberg; VMT, Bruchsal und Centerline, Wesel) and also some building contractors developed measuring systems targeted to the specific re-
quirements of CoJack. Their sensors continuously and automatically record, archive and transmit jacking parameters to the server of S & P Consult. Here CoJack retrieves the measurement data which are visualised together with the calculation results on the Internet. This ensures that the information is available promptly and in pre-processed form. It is even possible to follow jacking online in real time and react to changes at an early stage.

The integrated record of the currently applied jacking forces at the main jacking stations and intermediate jacking stations allows for a comprehensive and clear documentation of the forces calculated online with respect to a specific point in time and/or a specific jacking station.

The measuring systems work fully self-sufficiently, i.e. independently of the installed navigation system. Thus, they can be installed at each jacking site immediately after jacking started. A time-slot of only about 5 hours is needed in which jacking has to stop, but the installation can also be done in times when jacking pauses, i.e. at night or at the weekend.

Generally, the sensors include the following components:

- Inductive position sensors to measure the joint gap (Figure 8)
- Inductive position sensors to measure the curvature of the pipes (only in case of GRP-jacking pipes (Figure 8))
- Pressure sensors to measure the pressures at the jacking stations
- Inductive position sensors to measure the movements of the jacking stations
- Measuring wheel to determine the traversed jacking distance (Figure 9)
In selected pipe joints inductive position sensors are installed to supervise the joint gaps. At least three sensors are mounted and calibrated in each measurement joint. As a general rule, two or three measurement joints are aligned one after another. The inductive position sensors (white arrows in Figure 7) project to the interior of the pipe radially about 8 cm and have a length of about 35 cm. An additionally required box (red arrow in Figure 7) with the side lengths of 32 cm x 32 cm projects 20 cm to the interior of the pipe.

Figure 8 shows the arrangement of inductive position sensors to measure the joint gaps in reinforced concrete pipes. The illustration below shows the arrangement of the sensors in GRP-jacking pipes with additional inductive position sensors to measure the bending of the pipe.

After calibration is finished the system transforms the measured joint gap values to the positions springing line, crown and invert (Figure 7).
Pressure sensors are included in the hydraulic lines at the main jacking station and the intermediate jacking stations. These record the actually applied pressures and the joint measurement system calculates the resulting forces of the individual jacking stations (Figure 10).

All measured data are transmitted to the system computer via a single data cable and the controller unit and then displayed there. Data storage can be selected individually – time-dependent, station-dependent, or rather in dependence on the movements of the intermediate or main jacking stations.

1.4.3 Watching jacking work on the Internet

The results of the structural simulation via CoJack are represented on three visualisation levels:

- Computer at the construction site inclusive of a monitor and, if desired, backed up by an eye-catching signal light

- Short reports inclusive of a verbal evaluation of both the measured and calculated results and, where required, recommendations for jacking
The latest measurement data can not only be accessed and visualised on the computer at site, but also location-independently via Internet (Figure 11) on any individual computer with corresponding access rights (user name, password). Thus, not only the staff at the construction site, but also the construction supervisor and the client in the office are always informed on the current state of the jacking project inclusive of the most essential jacking parameters. Based on the latest measurement data the curves are continuously updated.

The diagrams on the Internet show:

- The course of the actually applied jacking force (inclusive of the latest limiting value)
- The course of the line curvature as joint gap difference between the springing lines (inclusive of the latest limiting value)
- The course of the cambers and sinks as joint gap difference between crown and invert (inclusive of the latest limiting value)

All curves can be displayed optionally over time or over the jacking length. The observer can zoom in any position to view it in greater detail.

The “signal light” represents a practical, simplified illustration of the results. Basically, jacking measures simulated via CoJack can be categorised in 4 case groups according to Table 1:
Table 1: Case groups of the simulation results

<table>
<thead>
<tr>
<th>Case group</th>
<th>Incident</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>All measured values were within the limits of the pre-calculation</td>
<td>none</td>
</tr>
<tr>
<td>B</td>
<td>Steering movements beyond the permissible limits</td>
<td>Continuation of jacking under new conditions</td>
</tr>
<tr>
<td>C</td>
<td>Exceedance of the permissible jacking force</td>
<td>Continuation of jacking under new conditions</td>
</tr>
<tr>
<td>D</td>
<td>Several steering movements beyond the permissible limits and exceedance of the permissible jacking force (recalculation)</td>
<td>Specific examination of certain pipes for damages</td>
</tr>
</tbody>
</table>

Green phase: All jacking specifications were kept and correspond to the pre-simulation. The pipe stress was always below the permissible level (case group A).

Yellow phase: The permissible steering movements (case group B) or the permissible jacking forces (case group C) were exceeded thus far that jacking would actually have to be interrupted or stopped. Using CoJack, it can be demonstrated that no overload occurred at the time of the exceedance. Furthermore, the structural simulation of the remaining distance yet to be traversed (forecast) verifies with the updated planning data and under consideration of the “pre-existing damage” of the pressure transfer ring that jacking can be continued and completed successfully under additional requirements.

Red phase: CoJack is designed to prevent entering the red phase. In this phase the pipe stresses exceed the permissible limiting values. The required safety regarding the strength of the concrete is not kept, because the value falls below the required level. Consequently, damages have to be expected. Until now, this case only occurred in recalculations of already completed critical pipe jacking measures that have not been accompanied by CoJack.

The functional principle of CoJack is illustrated in Figure 12. It shows the three process phases: Construction site with data acquisition and transmission (CoJack-Sync). The structural simulation (Cojack-Calc) and the output of the results for the construction site (signal light) and via Internet (CoJack-Online).

Further services are reports generation and, if desired, expert advice.
1.4.5 Example of CoJack application – Without CoJack it would have gone wrong

The controlling system CoJack has proven its worth in numerous jacking projects over the last years. In many cases CoJack allowed for a comprehensive and comfortable check of the jacking data on the Internet. In some jacking measures that turned out to be more problematic CoJack was clearly in great demand and could show that the relatively low investment in this controlling system can be very worthwhile.

This shall be illustrated by the following example:

Due to a steering error in a jacking measure of about 250 m length and several planned changes of curvature, angular deflections that exceeded the permissible extent by twice as much occurred in the pipe joints already 20 m behind the starting shaft. It was evident that all other pipes had to pass this sharp bend and that the longitudinal force would rise from pipe to pipe. The simulation
that was immediately created with an updated structural forecast for the entire jacking measure showed, of course, that owing to the steering error the permissible jacking force had to be lowered. Because of the small distance between the problem area and the starting shaft the pressure transfer rings positioned directly in front of the sharp bend were still so little deformed that they could accomplish their task of load distribution exceptionally well. For this reason the permissible jacking force could be lowered so moderately that jacking could be continued and successfully completed without delay.

Figure 13: Simulation accompanying jacking work (jacking state 170 m) for pipe 3 inclusive of planning data and structural forecast for the remaining distance (top: (black line: jacking load), (blue line: computed jacking load), middle: pipe string curvature, bottom: maximum pipe stress)

Figure 13 shows exemplarily for the third pipe at a jacking state of 170 m the stresses that already occurred at this point in time (to the left of 170 m) as well as the results of the structural forecast (to the right of 170 m). Due to the low jacking force the stresses in the sharp bend remained far below the permissible values. But the pre-damage due to plastic deformation of the pressure transfer ring was negligible, so that the permissible jacking force had to be adjusted only moderately.
Figure 14 shows the same situation shortly before jacking was completed for the most stressed pipe (pipe 50) that was directly in the sharp bend when the maximum jacking force was applied. The plastic deformation of the pressure transfer ring was fairly extensive in this case, but did not have consequences in the course of jacking, because the pipe had not to be pushed very far from there. It had reached its final position already before the second curvature. The measure could be completed successfully and without delay due to a timely accompaniment by CoJack and increased attention in steering.

Without CoJack the sharp bend at station 20 would not have been detected. Consequently, the permissible jacking force would not have been lowered. That would have resulted in over stress of and damages in the jacking pipes. If, despite a missing joint measurement, the sharp bend would have been realised, jacking would have had to be stopped for a structural check immediately. But the limited “normal” structural calculation would then have resulted in so small permissible jacking forces that after its stop the jacking measure would either have had to be continued with difficulty or not at all.

After a successful completion of the construction measure all parties involved shared the opinion that CoJack had saved jacking.
2 Summary

The method of utility tunnelling which involves pipe jacking and microtunnelling develops into the prevailing construction method at global level for drains and sewers in metropolises. As proven by numerous cases of damage on a national and international level, this very demanding technique of construction method requires expert competence which exceeds the latest standards in planning, construction and quality assurance.

Extensive practical experience has shown that these new specifications are fully met by the structural controlling system CoJack that was developed by Prof. Dr.-Ing. Stein & Partner GmbH and S & P Consult GmbH. CoJack provides a reliable possibility for a structural check for both clients and building contractors. It also aids decision-making in the evaluation of unforeseen events during jacking. Thus, CoJack guarantees both the avoidance of unnecessary down times and a maximum safety and economy due to more transparency and a greater scope of action on a basis of decision-making that has not been available yet.

In addition to clients especially quality-conscious jacking companies do also use CoJack to ensure their long-term economic success. They realised that CoJack is of particular value in optimising pipe jacking. It allows for the delivery of top quality and also a targeted use of technical measures, as e.g. the use of intermediate jacking stations, only in case these are absolutely required. Thus, CoJack makes jacking not only safer, but faster, more cost-effective and, consequently, more economic. These advantages are also used in the realisation of Europe’s biggest sewerage project “Emscher Kanal” by the earlier mentioned Emschergenossenschaft.

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