

## 1:1 simulation of pipe-jacking

Pipe-jacking has proven its worth as an economically rational and environmentally safe alternative to open-cut installation of new pipelines. The pipes are subjected to exceptional loadings during the installation procedure, however, particularly in case of directional (i.e., „non-straight“) pipe routes and difficult soil conditions. Test and inspection concepts applied up to now have been restricted in this context to the inspection of individual pipes and joints only, ignoring the pipe-string bed and curvature. This is the background to a research project conducted by the IKT – Institut für Unterirdische Infrastruktur (Institute for Underground Infrastructure), with financial support from the Ministry of the Environment of the German state of North Rhine-Westphalia and the Emschergenossenschaft.

A test system, using which jacking loads exerted on pipes and pipe joints, including the resultant bed stresses, can be simulated on a 1:1 scale, has been developed. The results obtained permit derivation of future recommendations for optimization of pipe joints, for planning and control of pipe-jacking operations, and for on-site instrumental support. One prime emphasis can be found in the field of stress analysis, also with a view to model concepts of pipe loadings during jacking.

### Background

Investments of around 500 million Euro annually are planned for construction of new drain and sewer systems in the German state of North Rhine-Westphalia alone [1]. A significant portion of this amount will be accounted for by the reconstruction of the Emscher system, costing approx. 150 million Euro/annum. Large sections of the Emscher drain and sewer system are to be constructed of large-diameter pipes of up to ND 2800 using pipe-jacking. This fact naturally increases even further the importance of the quality of the jacking pipes and joining methods

used. The risks of potential damage, such as cracking and spalling (Figure 1), must be reduced by means of appropriate Quality Assurance provisions.

North Rhine-Westphalia's Ministry of the Environment and the Emschergenossenschaft have taken this fact as the basis for the financial support of a corresponding IKT research project [2]. At the IKT, specialists from the fields of modelling, concrete technology and geological site surveying have developed a test system using which the jacking loadings exerted on pipes and pipe joints, and also the resultant bed stresses, can be simulated on a 1:1 scale.



Figure 1:  
Potential damage during jacking:  
a) cracking,  
b) internal spalling,  
c) external spalling

The experimental results will permit the future derivation of recommendations for the optimization of pipe joints, the planning and control of pipe-jacking operations, and for on-site mensu-



side hydraulic cylinders

rational supervision and support. One particular emphasis can be found in stress analysis. The starting point for this project is provided by experience of both typical and extreme loadings obtained in various individual pipeline construction projects either currently being implemented or already completed by Emschergenossenschaft and other system operators.

The basic test procedure, process control system and mensurational equipment were firstly validated in the context of model tests on a ND 400 pipe string consisting of five concrete test objects and then scaled up to large-scale tests with a nominal diameter of ND 1600 (ext. dia. = 2100 mm, L = 16 m). The specific assignment, the test concept and the test methods are discussed, and initial results examined, in the following report.

### Assignment

The idea for development of the IKT pipe-jacking simulator was conceived against the background of persistent uncertainties in the assessment of actual cases of damage and the risks of potential damage during pipe-jacking and of the broad technical discussion current at that time concerning suitable dimensioning concepts. Systematic studies into pipe-string reactions under pipe-jacking loadings were to be implemented

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in order to obtain knowledge and data on the performance of pipes and pipe joining methods, potentially critical jacking situations and the informational value of static modelling concepts. Figure 2 provides a comparative evaluation of the various theoretical concepts.

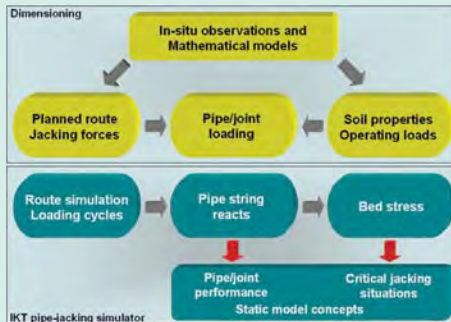


Figure 2: Comparative assessment of the dimensioning and IKT jacking-simulation task

## Dimensioning

The dimensioning of pipes and pipe joints for pipe-jacking is based essentially on in-situ experience and mathematical models. Basic planning principles, project implementation methods and Quality Assurance strategies thus develop continually from the experience gained in earlier pipe-jacking projects. Model engineering concepts, generally underpinned by analytical, empirical or numerical computation methods, for their part create correlations between on-site conditions and loads and the loadings exerted on the components. These explanatory concepts then make use of the corresponding assumptions concerning local boundary conditions for the purpose of overall description of individual projects. This applies, in particular, to the selection of the planned route, the jacking forces to be applied and anticipated operating loads, and to the soil properties to be assumed, on the basis, for example, of an expert geological assessment of the site. The loadings exerted on the individual pipes and pipe joints can then be determined mathematically and used as the input data for component dimensioning. The question of whether the dimensioning models and assumptions accord with the actual situation encountered in a particular project will, ultimately, remain unanswered in cases of trouble- and damage-free jacking. Only when damage occurs do inconsistencies become apparent, necessitating the augmentation of historical in-situ observations with further experience and, where necessary, critical analysis of individual model concepts.

## Concept

The concept of the pipe-jacking simulator augments the dimensioning concept of a „passive pipe“, i.e., the pipe exposed to external loads is dimensioned for the reactions to loadings induced from outside, in order to obtain a further, „active“ observation concept. It is known from in-situ observations of jacking operations (e.g. [3]) that the entire pipe string follows the jacking route driven by the shield in cyclical load steps. „Grinding off“ of movements through curves has not been observed, with the result that the jacking route, including planned curved elements and steering corrections, can be regarded as definitive for all pipes jacked. For any given route geometry, the pipe string is subjected in every load cycle (pipe advance) to the longitudinal loading necessary for jacking. An unrestrained pipe string will react with movements perpendicular to the route during the loading cycle, depending on pipe and pipe-joint characteristics and properties and the route situation. Corresponding bed reactions will occur if these movements are completely suppressed. The con-

Particular importance attaches in experimental jacking simulation to the selection of the jacking route to be simulated. It is important here, for example, to include in the simulation not only planned route elements, but also other routings permissible in-situ, such as deviations and steered curves, for example. Figure 3 shows by way of example a corresponding route which includes not only the planned straight and curved sections, but also the „Deviation from target route“, „Correction“ and „Return to target route“ cases (see [4]).

The central aim of the research project was, therefore, the development of a test system using which the reactions of the jacking pipes, including their joint systems, could be observed during simulated jacking on a specified route and the maximum anticipated bed reactions evaluated as input data for the site geological survey and static analysis. The question of the interaction between the heading shield and the soil, and that of lubrication within the annular space thus generated, were not the subject of the study.

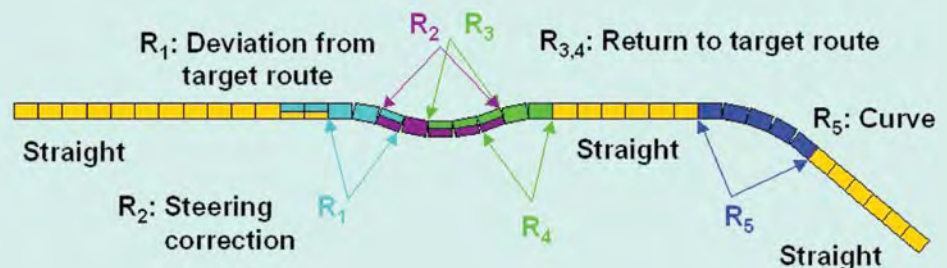


Figure 3: Route elements in the example, not to scale

cept of the pipe-jacking simulator makes use of this „active“ behaviour of the pipe string under exposure to axial loading: a five-pipe string is exposed under a simulated route geometry to an axial load and the bed reactions necessary in this situation are determined. These bed reactions can then be regarded as an initial indication of the maximum possible in-situ soil reactions for given pipe and pipe-joint characteristics. 1:1 simulation using actual pipes, pressure-transmission equipment and sealing elements also takes account of geometrical imperfections (e.g. concrete surface) and non-linear elasto-visco-plastic materials properties and characteristics (e.g. wood, plastics), which are scarcely susceptible to mathematical description but which, even under subjection to major deformations and after prolonged deformation histories, are in many cases decisive.

The following items were also to be studied for the purpose of practical application:

- Pipe joining technology: The selection of the particular pipe-joining method has a great influence on force transmission and the sealing function of the pipe string. Particular importance attaches to the means of pressure transmission used. The influences exerted by materials characteristics and properties on the performance of the pipe string under load were to be identified and recommendations derived for selection and testing of the material.

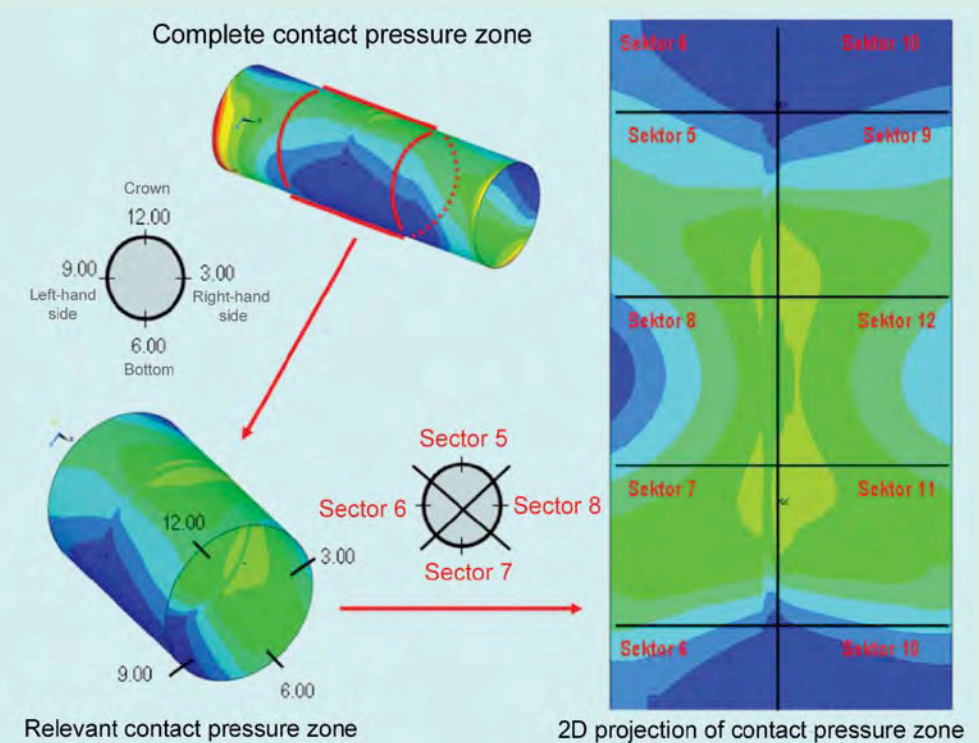
- Jacking planning and steering: Information on possible effects of steering influences and, if appropriate, recommendations on permissible tolerances, were to be derived from simulation of jacking through curves and steering movements.
- On-site mensurational supervision and support: A broad range of modern measuring systems (including pressure mapping films) was used for the first time in these tests for registration of jacking movements and loadings under 1:1 conditions. The mensurational suitability of this equipment for use under practical pipe jacking conditions was to be investigated and evaluated.

### The pipe-jacking simulator

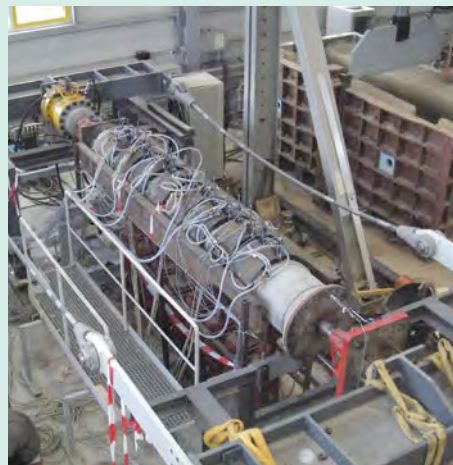
A 1:1 test system, the pipe-jacking simulator, was developed and integrated into the large-scale test facility operated by the IKT – Institute for Underground Infrastructure – in order to perform the tasks formulated above. This large-scale test facility serves during the project as an „abutment“ structure for the absorption of loads and as a containment in case of unforeseen load reactions during the running-in phase. Setting-up at a different location after completion of the project is possible in principle and is, indeed, targeted.

During testing, a pipe string consisting of five reinforced-concrete jacking pipes of nominal diameter ND 1600 and equipped with the above-mentioned instrumentation, is exposed to approximately authentic jacking forces. The pipe-string and bed reactions are registered mensurationally for various pressure-transmission equipment and route situations and possible influences on the pipe-joining technology used are estimated.

The dimensioning of the test facility, including the hydraulic cushions selected for the pipeline bed, was based on geological site observations from previous projects [5] and predictive computations using the Finite Element Method (FEM) [6]. The newly developed instrumentation for performance of the tests, and the basic test sequence and procedure, were subjected to validation in model trials performed on a ND 400 pipe string consisting of five concrete test objects. The overall concept for the 1:1 scale tests (reinforced-concrete ND 1600 pipes) was completed in the spring of 2006 (Figures 4 and 5).



a) FEM computations [6]



b) ND 400 model tests



d) 1:1 jacking station (4 x 2 MN),



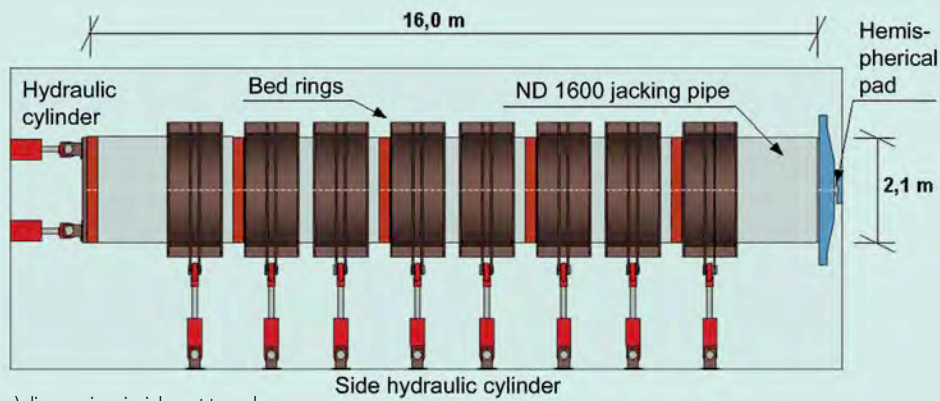
c) 1:1 ND 1600 (dia. = 2100 mm, L = 16.0 m) pipe string

Figure 4: Preliminary investigations and pipe-jacking simulator, scale 1:1

The simulator consists essentially of the following components: Jacking station, bearing stand track, pipe guide, side control unit, abutment structure, and five jacking pipes (Figure 5a).

The jacking station consists of four 2 MN hydraulic cylinders (rams) which can be addressed for both path control and force control and permit a maximum jacking force of 8 MN.

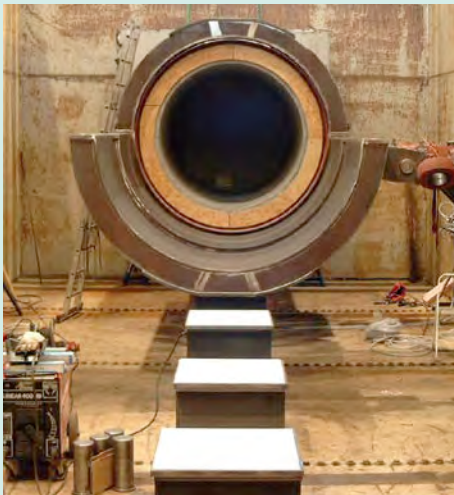
# Simulation of pipe-jacking



a) diagram in principle, not to scale



b) jacking station



c) bearing stand track



d) steel pipe-cushion ring

This figure accords with the maximum forces needed for jacking of larger pipe lengths. Maximum force was restricted in the test, since larger forces are, even in practice, avoided by means of the use of intermediate jacking stations.

The jacking force is transmitted into the pipe string via a steel thrust ring. The connection of the hydraulic cylinders to the thrust ring is of flexible type, both horizontally and vertically (Figure 5b).

The pipes are supported by means of water-filled shell segment pressure cushions. These are positioned in the vicinity of the pipe's springline (cushion dimensions 1.2 m x 1.2 m), in particular, for mensurational registration of the bed reactions. The underside cushions serve only for support of the pipe, while the small crown cushions (Figure 5e) provide protection against unforeseen upward-thrusting loads. Two circumferential steel rings with internal diameters of 2170 mm form for each pipe the abutments for the hydraulic cushions, which are located in the 35 mm annular gap between the jacking pipe and the steel ring (Figure 5d). The steel rings are assembled from two half-shells in order to simplify installation of the jacking pipes. The lower half-shell in each case is positioned on a steel table with a PTFE („Teflon“) support pad, in order that the pipes can be positioned virtually friction-free in the horizontal direction (Figure 5c). Electrical control valves on the cushion supply and return lines are used for charging and discharging of the hydraulic cushions, electronic pressure sensors for registration of pressure.

Various jacking conditions can be selected by means of horizontal positioning of the pipe guide using eight 1000 kN hydraulic cylinders. These

are flexibly linked to the steel rings by means of brackets and bolts and are also connected to the side wall of the large-scale test facility (Figure 5f). The valves, position encoders and pressure sensors are used for control of the hydraulic cylinders; a specially programmed processing system permits simultaneous coordinated activation of all hydraulic cylinders.

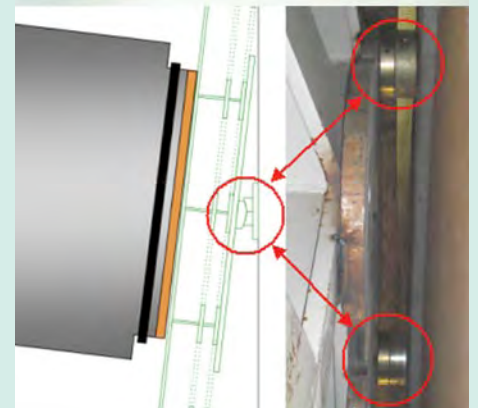
The abutment structure consists of a steel plate reinforced on its rear side, which is supported against the rear wall of the IKT test facility by



e) shell segment pressure cushion



f) side hydraulic cylinder



g) abutment

Figure 5: ND 1600 (dia. = 2.1 m) jacking simulator, force transmission and bed

means of two approximately hemispherical metal pads. The hemispherical pad support system permits rotation of the abutment structure about the vertical axis (Figure 5g), with the result that the „Straight“, „Deviation from target route“, „Correction“, „Return to target route“ and „Curve“ route elements shown in Figure 3 can be simulated in the form of successive

jacking situations as shown in Figure 6. All tests are controlled, and observed in detail, using the diverse range of measuring methods and devices installed. These include inductive position encoders, rope position encoders, measuring pressure sensors, pressure mapping films and measuring strain gauges (Figure 7). The five ND 1600 reinforced-concrete jacking pipes, with a length of 3.2 m, thus themselves essentially function as instrumentation systems, and constitute a component of the overall test apparatus.

A total of 160 measuring strain gauges were applied in the form of 0°/45°/90° rosettes to the pipes for measurement of strain on the pipe circumference. Strain is recorded on the inner side of the pipes at the eighth and quarter points, and on the outer side at the eighth points of the measuring pipes (Figure 7a).

Three inductive position encoders were fitted at intervals of 120° in each pipe joint in order to record angular deflection between the pipes. The position encoders are bolted to the reduced-diameter end of the pipes and register distance from a steel bracket fixed in the mating pipe socket (Figure 7b).

Ten Tekscan film-type pressure sensors were inserted into the pressure-transmission surfaces of the central pipe in each case for measurement of contact pressure in the pipe joints. These pressure mapping films make it possible to record in qualitative terms the pressure distribution between the pressure-transmission element and the pipe socket (Figure 7c+d).

Both the hydraulic cylinders of the jacking station and those of the side steering unit are

equipped with rope position encoders for steering and documentation of cylinder travel and with force sensors for adjustment and evaluation of the jacking force and possible transverse bed reactions.

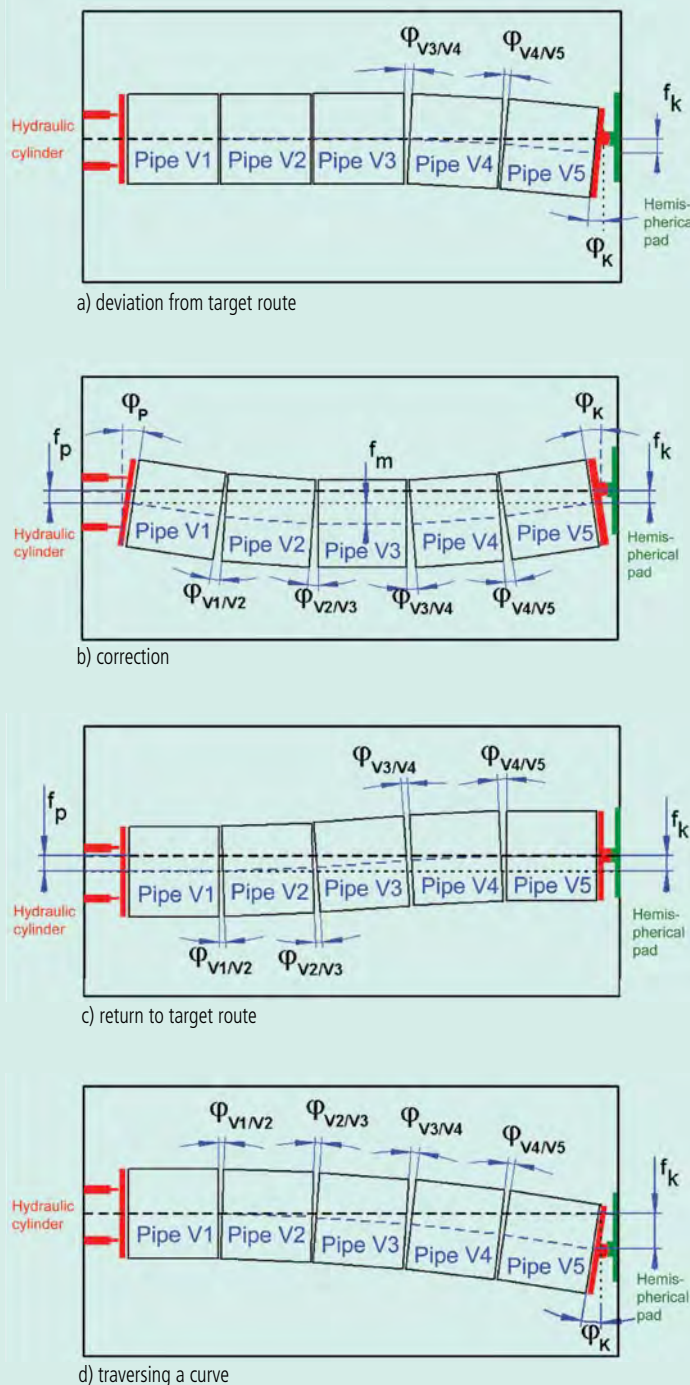
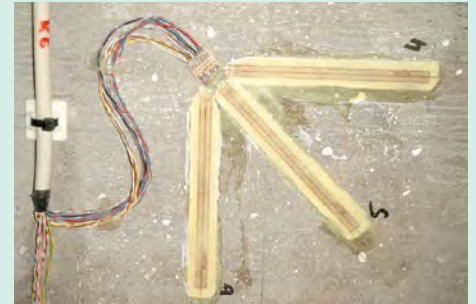


Figure 6: Jacking simulation, not to scale



a) strain gauges



b) position encoder



c) pressure measuring films



d) view into the pipe string

Figure 7: ND 1600 (dia. = 2.1 m) jacking simulator – instrumentation

# Simulation of pipe-jacking

## Test program and initial results

The pipe-jacking simulator was used for an extensive program of tests. Comparative tests are, for example, being applied to test various pressure-transmission elements (OSB [oriented strand

board] slab, natural wood, plastic) and their influence on loadings in various route configurations and critical jacking situations. Customary assumptions from static calculations are critically analyzed, as is the informational value of the

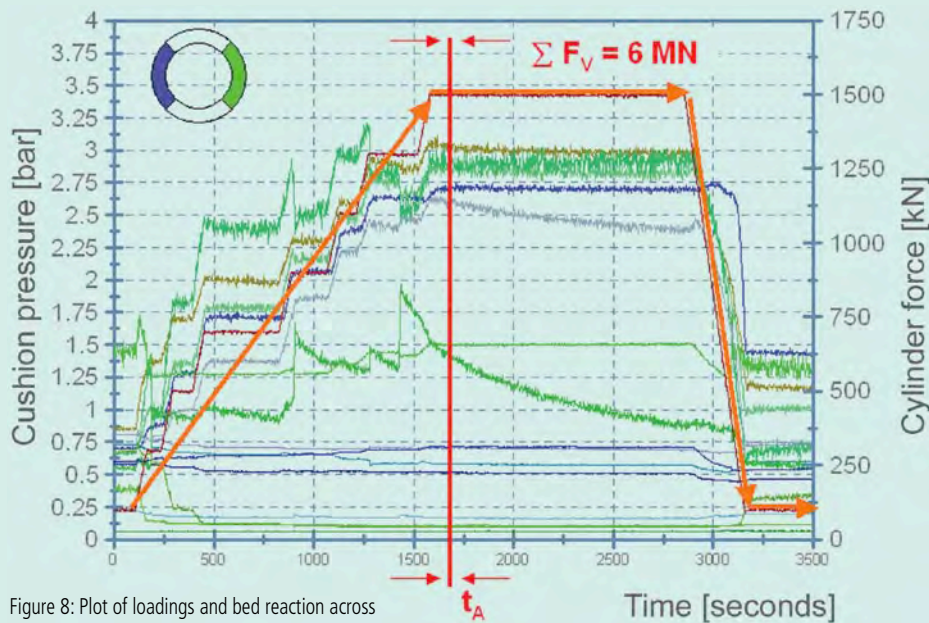


Figure 8: Plot of loadings and bed reaction across test period, time of analysis  $t_A$

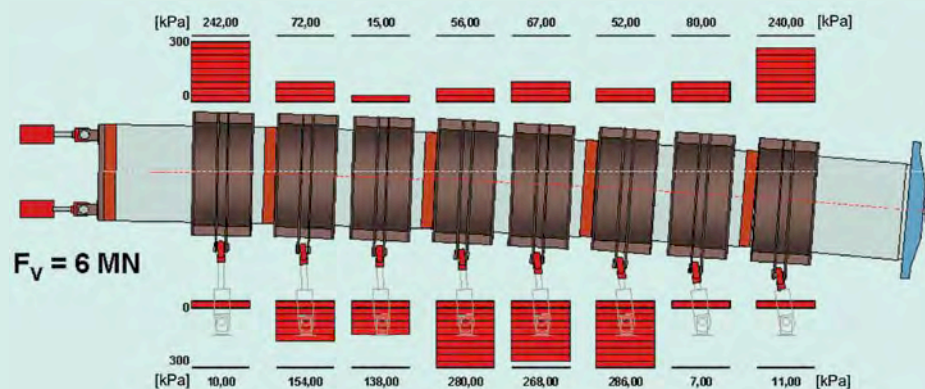


Figure 9: Specimen view of necessary bed reaction for transition through a curve at time  $t_A = 1650$  s, not to scale

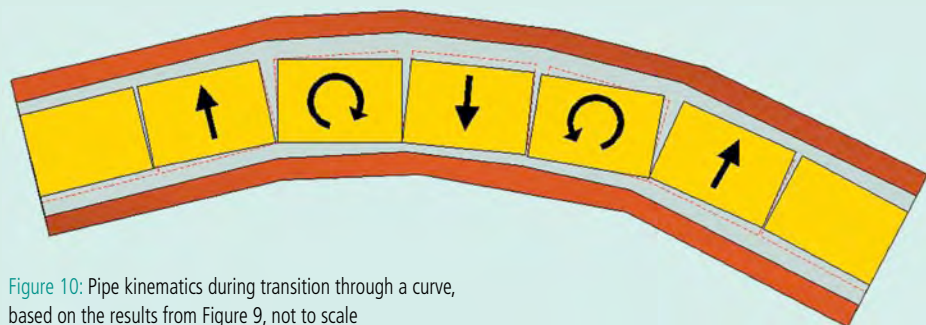


Figure 10: Pipe kinematics during transition through a curve, based on the results from Figure 9, not to scale

mensurational systems deployed during installation operations. These tests were completed in 2007. Evaluation of results for the „Negotiation of a curve” section as shown in Figure 3 is examined below by way of example. The overall route simulation includes all of the jacking situations shown in Figure 6, with a total of 39 load cycles. In the present case, an OSB slab of a thickness of 25 mm was used as the pressure transmission element. Figure 8 shows the plot of loading and cushion pressure against test time and defines the point in time of an instantaneous analysis, the results of which are summarized in Figure 9 by way of example. The cushion pressures shown correlate to the measured, and therefore necessary, bed reactions for the jacking state set at time  $t_A = 1650$  s.

The pressure distribution shown in Figure 9 clearly indicates that the entire pipe curve is held against the outer side of the curve at the starting and finishing points of the curve. The pipes located within the course of the curve are subjected to a restraining and retarding bed reaction on the inner side of the curve, however. Figure 10 shows the pipe kinematics derived from this, i.e., the movements which are to be anticipated in the case of a deformable bed. The central pipes have a tendency toward a straight alignment, with the consequence that they rotate relative to the first and last pipes. As a result, it is necessary to anticipate irregular external loadings on individual pipes and corresponding transverse-force loadings in the pipe joints. These results gain even more significance as a result, in particular, of the fact that grouping of pipes to form short straight sections during negotiation of curves is also reported by experts from jacking practice. Corresponding measurements have, however, up to now been restricted only to individual cases, and the phenomena observed have generally been classified as a special case.

The measured data obtained for further jacking situations has been evaluated, tests were also conducted using different pressure-transmission elements, and the bed reactions observed has been analyzed and evaluated. Corresponding results are now available.

## Conclusions

A 1:1 scale test system, using which jacking loadings on pipes and pipe joints, including the resultant bed stresses, can be reliably simulated, has been developed in the form of the pipe-jacking simulator. The initial test results permit the derivation of the following conclusions:

- As a result of the special geometrical and mechanical properties of the joining methods used, jacking pipes are extremely complex components. The pipe string is capable under jacking loads of provoking bed reactions, the magnitude of which depends on the route configuration and the selection of oversize cut.
- The negotiation of curves, in particular, must be regarded as a critical jacking state, in view of the loadings exerted on the individual pipe joints. Non-homogeneous bed reactions and corresponding transverse-force influences must be anticipated.
- Diverse loadings on the pressure-transmission element must be anticipated. Its properties will then, for their part, be capable of significantly determining the bed reactions and pipe loadings to be expected. Special importance therefore attaches, with respect to reduction of the risks of damage, to the pressure-transmission element.

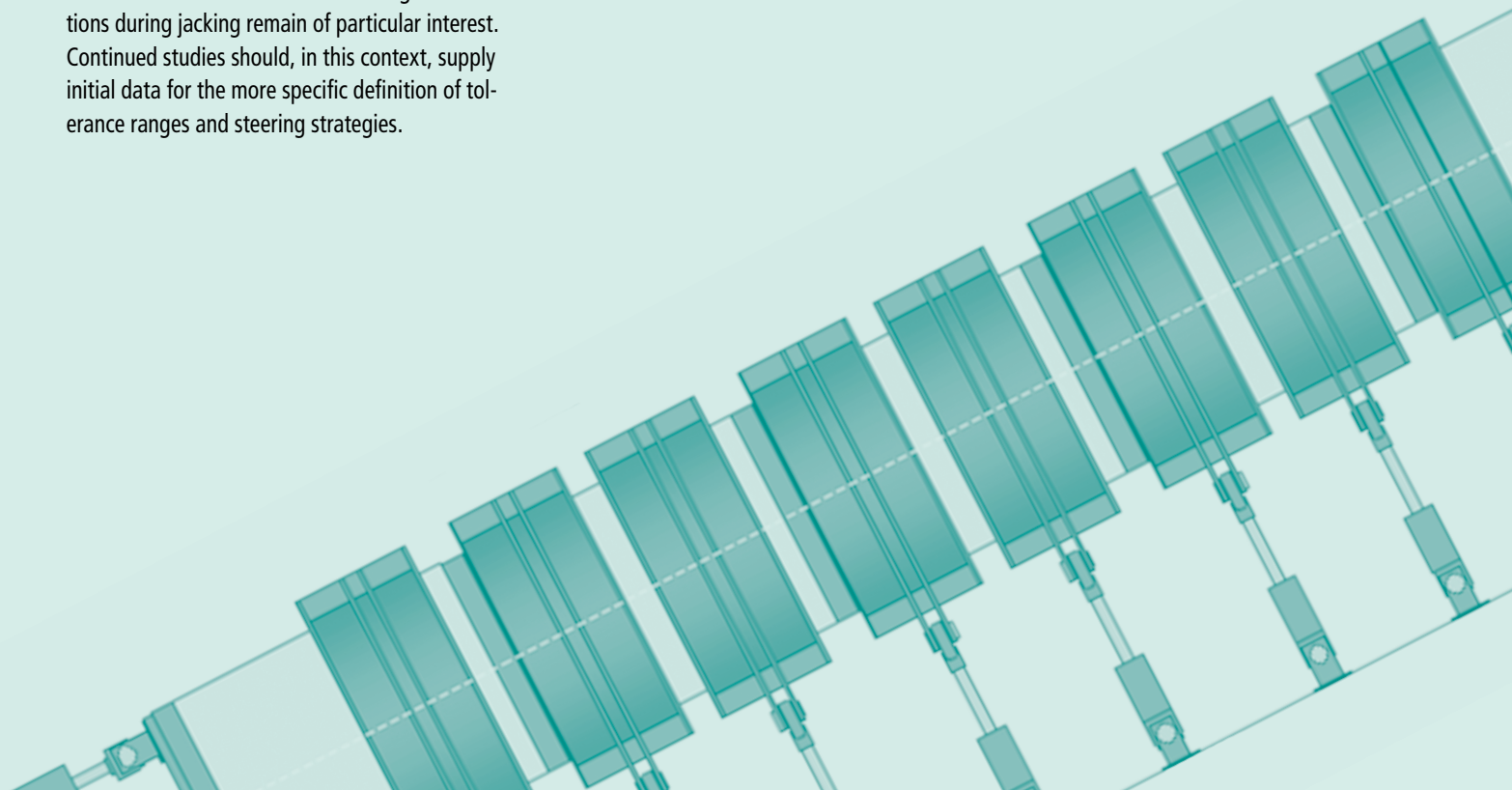
Observation and evaluation of steering corrections during jacking remain of particular interest. Continued studies should, in this context, supply initial data for the more specific definition of tolerance ranges and steering strategies.

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Source: Bosseler, Liebscher, Redmann: Simulation von Rohrvortrieben im Maßstab 1:1  
in: 3R international (45) 12/2006



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**IKT - Institute for Underground Infrastructure** is a research, consultancy and testing institute specialized in the field of sewers. It is neutral and independent and operates on a non-profit basis. It is oriented towards practical applications and works on issues surrounding underground pipe construction. Its key focus is centred on sewage systems. IKT provides scientifically backed analysis and advice.

IKT has been established in 1994 as a spin-off from Bochum University, Germany.

The initial funding for setting up the institute has been provided by the Ministry for the Environment of the State of North-Rhine Westphalia, Germany's largest federal state.

However, IKT is not owned by the Government. Its owners are two associations which are again non-profit organizations of their own:

**a) IKT-Association of Network Operators:**  
Members are about 100 cities, among them Berlin, Hamburg, Cologne and London (Thames Water). They hold together 66.6% of IKT.

**b) IKT-Association of Industry and Service Providers:** Members are about 60 companies. They hold together 33.3% of IKT.

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IKT is located  
ca. 30 min. off Düsseldorf  
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Published: April 2008  
Circulation: 5.000 copies  
Protective charge: 19,95 €