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**Stoesser, Thorsten; Rodi, Wolfgang; Olsen, Reidar**

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# Large Eddy and RANS Simulations of the Flow over Dunes

Thorsten Stoesser, Wolfgang Rodi und Nils Reidar Olsen

Im vorliegenden Beitrag werden Large Eddy Simulationen (LES) der Strömung über idealisierte Sanddünen vorgestellt. Die Dünengeometrie sowie die Randbedingungen wurden analog zu Laborversuchen gewählt, sodass die Güte dieser Large Eddy Simulationen mit Hilfe eines Vergleichs zu den gemessenen Daten abgeschätzt werden kann. Die Methode der Large Eddy Simulation ist sehr rechenintensiv und für praktische Fragestellungen im Rahmen des Wasserbaus noch 1nicht geeignet. LES wird z Zt. hauptsächlich in der Turbulenzforschung eingesetzt um neue physikalische Erkenntnisse von räumlich hochkomplexen, instationären, turbulenten Strömungsmechanismen zu erhalten. Im Rahmen dieser Untersuchungen wurden daher auch Reynolds-Averaged Navier Stokes (RANS) Berechnungen für die gleichen Konfiguration durchgeführt und die Ergebnisse mit den LES und Laborexperimenten verglichen. Das zeitlich gemittelte Strömungsfeld kann zufriedenstellend mit einer statistischen Rechenmethode der Strömung (RANS) prognostiziert werden. Jedoch ergeben sich Unterschiede beim Vergleich der turbulenten kinetischen Energie und den Sohlschubspannungen, da das RANS Modell die hochgradig instationären Vorgänge der Strömungsablösung an der Dünenkante und das Wiederanlegen auf dem Rücken der Folgedüne nicht adäquat wiederspiegeln kann. Die Erkenntnisse aus den Large Eddy Simulationen sollen in eine verbesserte RANS Modellierung einfließen, sodass eine erhöhte Genauigkeit bei der Vorhersage von Strömung und Morphologie in der Praxis gewährleistet werden kann.

## 1 Introduction

A flow of sufficient turbulence intensity generally initiates the motion of bed material in an alluvial channel. In the case of sand-bed rivers this motion usually results in dune or ripple formations at the channel bottom. The flow over dunes has been studied widely, to understand the effect of bed shape on the flow and the mechanisms of bed and suspended load transport of sand bed rivers (most recently by Maddux *et al.,* 2003a and 2003b). Because of the bed deformation, mean flow characteristics, distributions of turbulent velocities, bed shear stresses, and turbulence intensities differ significantly from those over smooth beds (e.g. McLean *et al.,* 1999; Zedler and Street, 2001). A dune formation causes the overlying flow to separate at the dune crest, creating a large separation zone on the leeside of the dune. Bordering the separation zone is a turbulent shear layer associated with large-scale eddies which travel along that shear layer and towards the surface while dissipating. The flow reattaches approximately 4-6 dune heights downstream of the crest (Engel, 1981). Downstream of the reattachment point a new boundary layer is formed and grows as the flow accelerates towards the next dune crest.

Numerous experimental studies were undertaken in the past in order to study the flow over dunes (e.g. most recently by Polatel et al., 2005; Hyun *et al.*, 2003; Maddux *et al.,* 2003a, 2003b; Lyn, 1993; Mierlo and Ruiter, 1988). However, these experimental investigations are either of limited spatial resolution or are restricted to time-averaged quantities along selected measurement verticals. Numerical simulations provide a complete picture of these flows and may be used to complement experimental investigations, as parametric studies, or even for the exploration of new flow physics and mechanisms. Only a limited number of numerical studies of flow over dunes exist. Yoon and Patel (1996) presented calculations of the flow over dunes based on the solution of the Reynolds-Averaged Navier-Stokes (RANS) equations, and reported a good agreement between computed and measured time-averaged velocities. More recently, Patel and Lin (2004) showed results of both RANS computations and Large Eddy Simulations, and compared mean velocities and turbulence statistics to those measured by Hyun et al. (2003). They also concluded that a RANS model captures much of the mean velocity information but fails to model the effect of the large-scale flow structures on the turbulence statistics. However, though the available computing power and memory capacities of modern computers are rapidly increasing, LES is still restricted to Reynolds numbers below $10^5$, which has been shown recently during a turbulence model workshop (11th ERCOFTAC/IAHR Workshop on Refined Turbulence Modelling, Chalmers University of Technology, 2005). This means that for the computation of practical flow problems for engineering purposes RANS methods are still of great interest and deficits need to be identified and ideally be removed.

In this paper, we present the results of Large Eddy Simulations (LES) as well as simulations that are base on the solution of the Reynolds-Averaged Navier-Stokes equations (RANS) of a channel flow over a train of two-dimensional fixed dunes. Geometry and boundary conditions were selected in analogy to laboratory experiments as reported by Polatel (2005). The dune height is $k = 20$ *mm*, and the dune wavelength is $\lambda = 400$ *mm*, so that $\lambda/k = 20$, which is typical of many previous studies. Several water-depth-to-dune-height-ratios $h/k$ were investigated, however here we focus on $h/k=4$. The results of the computations are compared with Laser Doppler Velocimetry (LDV) measurements taken at six verticals along the geometry. The Reynolds number, based on the bulk velocity <U> and the average flow depth *h,* is approximately 22000. Time-averaged flow velocities, kinetic energy and wall shear stresses along the dune bed are compared and the quality of the RANS simulations is evaluated.

# 2 Numerical Models

## 2.1 LES Model

The LES code, LESOCC developed at the Institute for Hydromechanics, University of Karlsruhe (Breuer and Rodi, 1996) was used to perform the large-eddy simulations. LESOCC solves the filtered Navier-Stokes equations discretised with the finite-volume method, and uses a non-staggered grid on curvilinear body-fitted coordinates. The convective and diffusive fluxes are approximated with central differences of second-order accuracy. The Poisson equation for coupling the pressure to the velocity field is solved with the SIP method of Stone (1968). Time advancement is achieved by a second-order, explicit Runge-Kutta scheme in LESOCC. The subgrid-scale stresses appearing in the filtered Navier-Stokes equations are computed using the dynamic approach of Germano et al. (1991). The no-slip boundary condition is used on the walls where the first grid point is placed at a distance in wall units of approximately $z^+=1$. The computational domain for the LES calculations spanned 1 dune length $\lambda$ in streamwise, 2 water depths $h$ in spanwise and $1h$ in vertical directions, respectively. The grid consisted of *500* x *80* x *120* grid points in the three directions, streamwise, spanwise and vertical. The grid spacing in terms of wall units was $\Delta x^+\approx 30$ in streamwise direction, $\Delta y^+\approx 45$ in spanwise direction and approximately 1 for $\Delta z^+$ near the dune surface. Periodic boundary conditions were applied in the streamwise and spanwise directions. The free surface was treated as a flat plane of symmetry (with zero stress condition).

## 2.2 RANS Model

The model SSIIM (Olsen, 2005) is employed to perform the time-averaged RANS simulations. This model solves the Reynolds-Averaged Navier-Stokes equations with the finite-volume approach on a structured non-orthogonal grid. The SIMPLE method couples the pressure to the velocity field and the standard k-epsilon turbulence closure models the Reynolds Stresses appearing in the RANS formulation of the Navier Stokes equations. A second-order upwind scheme is employed to model the convective terms in the Navier-Stokes equations, whereas diffusive terms are approximated with a central scheme. The no slip condition for smooth walls are used at the bed, and a zero gradient boundary conditions is applied at the water surface. The grid size consisted of

100x300 cells, in the vertical and streamwise direction, respectively. The time-averaged flow field is constant in the lateral direction, hence the RANS computations were performed as a two-dimensional simulation. The grid covered one dune length, and a cyclic boundary condition was used for the inflow parameters.

## 3 Results and Discussion

### 3.1 Mean Flow Velocities

Figure 1 presents the distribution of time-averaged velocities over one wavelength of the dune. The flow separates at the dune crest, and reattaches just before the bed elevation increases towards the next crest. The flow recovers after a large recirculation zone, and develops a new boundary layer over the stoss-side of the next dune. The reattachment length of the flow is $l = 5.4k$. Figure 2 shows the comparison of the LES and RANS simulation to the experimental data at the six measurement verticals for the streamwise velocity component. As can be seen, overall prediction of the mean velocity is in very good agreement to the observed data for both simulations. The velocity profile of the formed boundary layer at the dune crest is in conformity to the observed one (Vertical1 – V1). As visible from the second vertical (V2), the strength and the vertical extent of the recirculation bubble seems better predicted by the LES model. The length of the recirculation zone and thus the point of reattachment is correctly calculated by the LES and but grossly underestimated by RANS (see locations V4 and V5). This can also be seen from Figure 3 where mean streamlines are plotted together with the line $<U>=0.0$ for both LES and RANS. The redevelopment of the boundary layer (V6 and V1) seems slightly better predicted by the RANS model.

### 3.2 Kinetic Energy

As was shown in a previous paper (Stoesser et al., 2005) the agreement of turbulent normal Reynolds stresses $u'u'$, $w'w'$ and Reynolds shear stresses $u'w'$ with the experimental data is very satisfactory. Hence, the kinetic energy as predicted by the LES can be taken to evaluate the RANS models capabilities to predict the turbulence of this flow. In Figure 4 the distribution of the kinetic energy of the LES (with $kin=0.5*(u'u'+v'v'+w'w')$) is compared to the kinetic energy from the RANS simulations. Most of the turbulence production occurs in the shear layer, where the flow moves over the recirculation bubble. There the peak of the kinetic energy contours can be seen. The RANS model slightly underpredicts the value of the peak by about 10% and the area of high kinetic energy is shifted towards the bed. Also the RANS model generally overestimates the kinetic energy over the rest of the flow geometry. This smearing effect is well known for eddy viscosity models.

### 3.3 Wall Shear Stress

Figure 5 presents the distribution of the wall shear stress along the dune bed over one wavelength. Since the first grid point is placed in the viscous sublayer the wall shear stress can be evaluated from $\tau=\rho\nu(\langle dU\rangle/dz)$. The overall match between both lines is apparent, however the extent and the strength of the recirculation is underpredicted by the RANS computations.

## 4 Conclusions

In this paper we have presented the results of RANS and Large Eddy Simulations of a channel flow over two-dimensional dunes. The time-averaged velocity calculated by both numerical methods show very good agreement with the observed data, and all the major features of the turbulent flow over dunes are correctly predicted. Whereas LES provides an accurate prediction of the turbulence quantities, RANS simulations with eddy viscosity turbulence models generally show deficits, due to an excessive smearing effect of this model model. Nevertheless, the distributions of kinetic energy as well as bed shear stresses are still predicted reasonably well.

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**Autoren:**

Thorsten Stoesser
Universität Karlsruhe (TH)
Institut für Hydromechanik
Kaiserstraße 12
76128 Karlsruhe
Tel.: 0721/608-3118
e-mail: stoesser@ifh.uka.de

Wolfgang Rodi
Universität Karlsruhe (TH)
Institut für Hydromechanik
Kaiserstraße 12
76128 Karlsruhe
Tel.: 0721/608-3535
e-mail: rodi@ifh.uka.de

Nils Reidar Olsen
The Norwegian Institute of Technology
Department of Hydraulic and Environmental Engineering,
S.P. Andersensvei 5, N-7491 Trondheim
Norway
e-mail: nils.r.olsen@ntnu.no

# 6 Figures

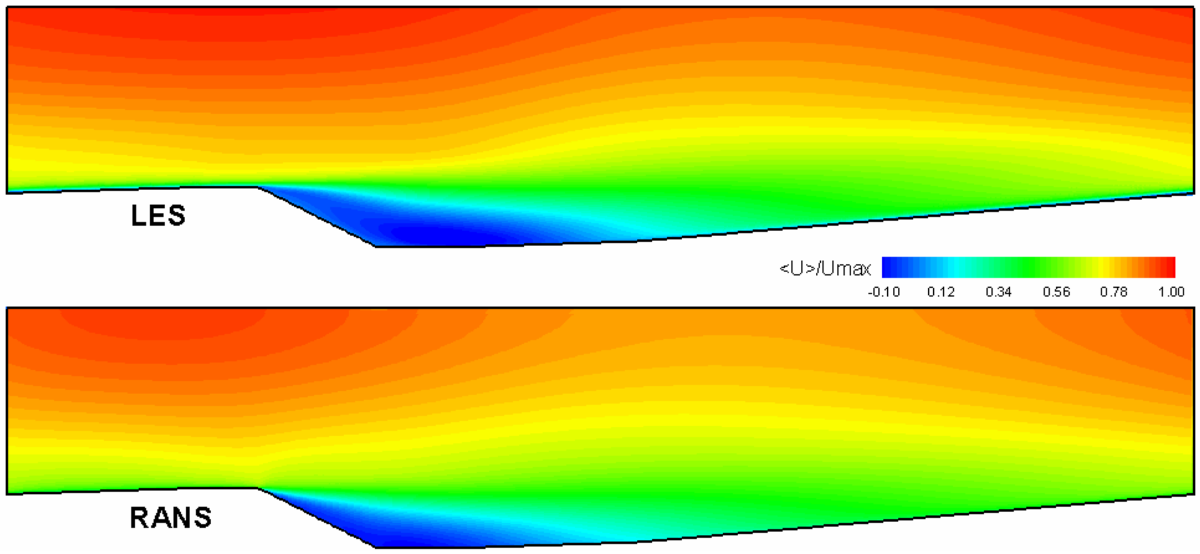



**Figure 1** **Distribution of mean streamwise velocities for the LES (top) and RANS (bottom) calculations**

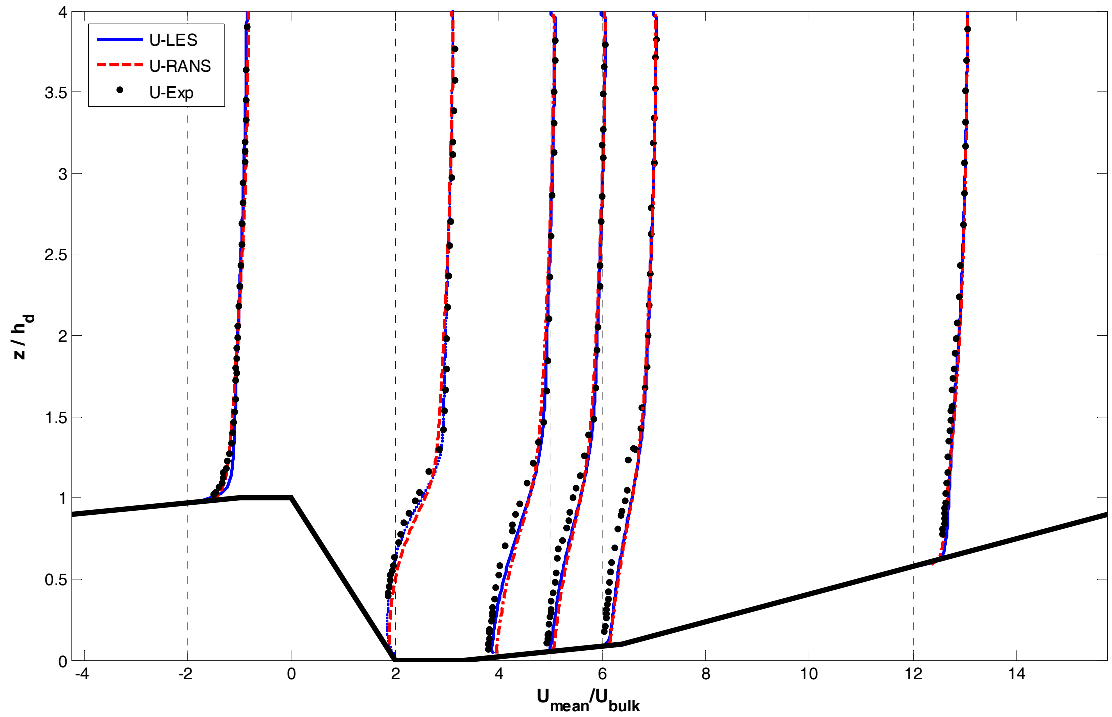



**Figure 2** **Distribution of mean streamwise velocities along the six verticals (V1 – V6)**

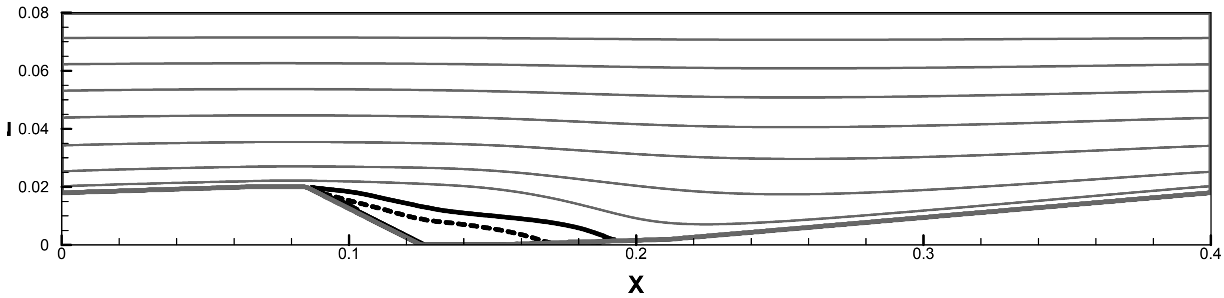



**Figure 3** **Streamlines from the LES and zero velocity line indicating the point of reattachment (dashed line=RANS, solid line=LES)**

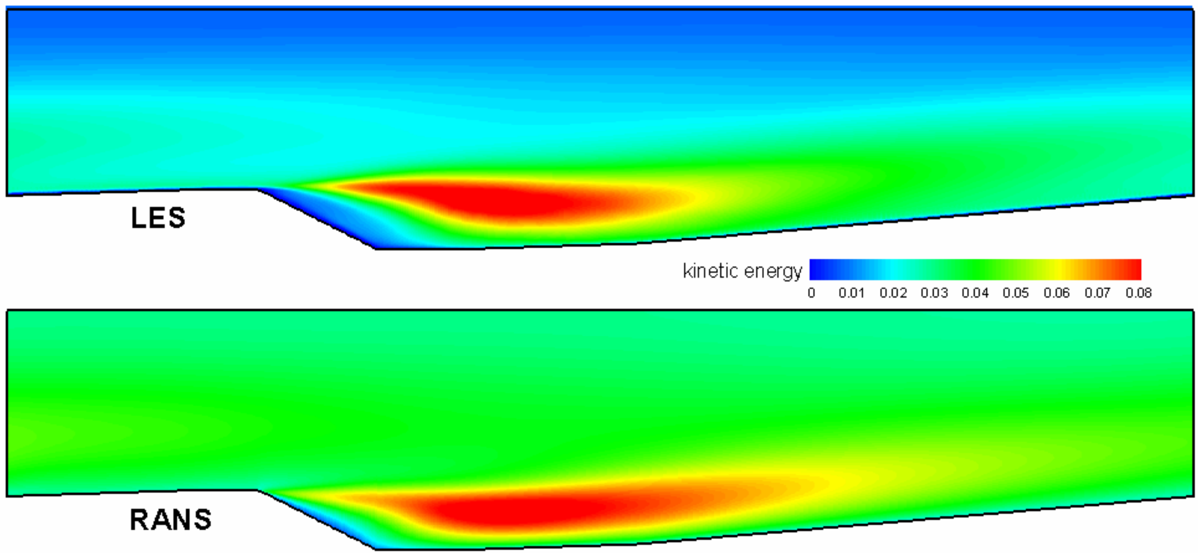



**Figure 4 Distribution of the kinetic energy for the LES (top) and RANS (bottom) calculations**

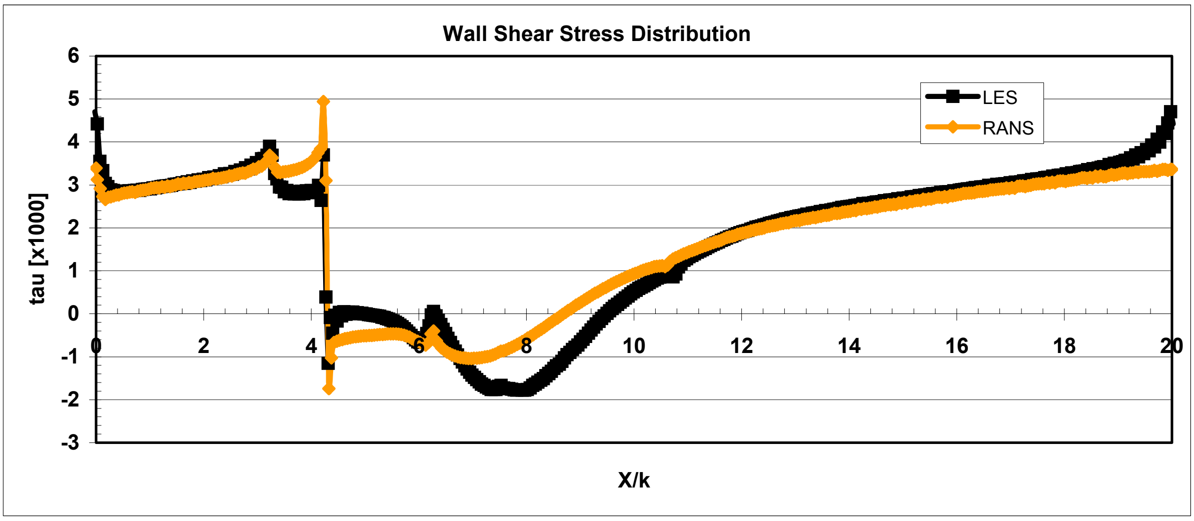
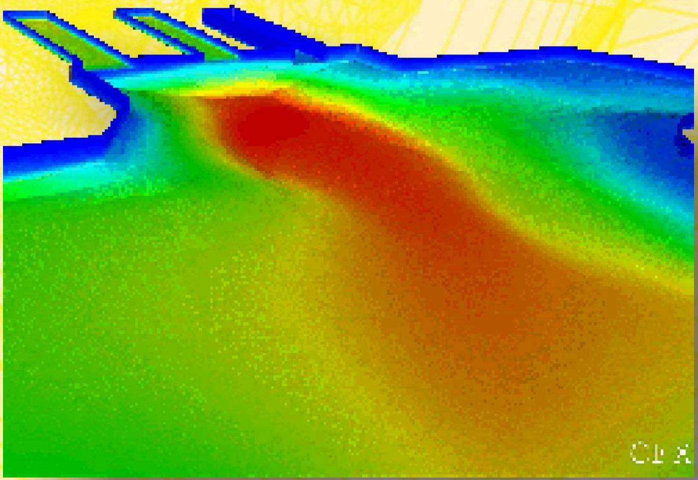
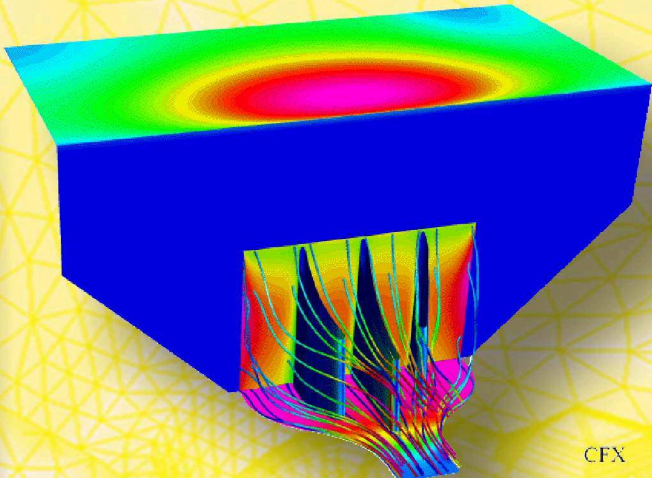



**Figure 5 Distribution of mean wall shear stress along the dune bed**

# ANSYS Struktur- und Strömungssimulation im Wasserbau




Sedimentablagerung in einem Frischwasserbecken




Einlaufbereich einer Pumpturbine

Umströmung wasserbaulicher Anlagen

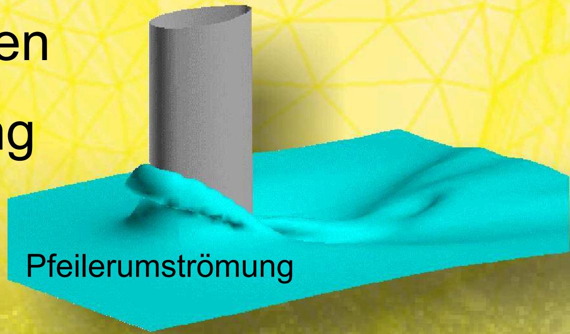
hydrodynamische Bauwerksbelastung

Sedimenttransport und -ablagerung

Kavitation

Erosion

und vieles mehr




**ANSYS Germany GmbH**
**Staudenfeldweg 12**
**D-83624 Otterfing**
**Tel.: +49(0)8024 9054-0**
**www.cfx-germany.com**
**E-Mail: cfx-info-germany@ansys.com**