Long-wave-induced flows of cohesive sediments

Photographed by Clark Little

Bondevik et al. (2003) EOS

7 Nov, 2013

Yong Sung Park
y.s.park@dundee.ac.uk

EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 84 NUMBER 31
5 AUGUST 2003
PAGES 289–300

Record-breaking Height for 8000-Year-Old Tsunami in the North Atlantic

PAGES 289, 293

One of the largest Holocene sub-marine slides mapped on Earth is the Storegga slide offshore Norway [*Bugge*, 1987] (Figure 1). Approximately 3500 km^3 material slid out and generated a huge tsunami dated to about 7300 ^{14}C yr BP [*Bondevik et al.*, 1997a], or ca 8150 calendar years BP. The tsunami is known from onshore deposits in Norway [*Bondevik et al.*, 1997a], on the Faroe Islands [*Grauert et al.*, 2001], and in Scotland [*Dawson et al.*, 1988]. Of these, the tsunami deposits in western Norway reaches the highest elevation, indicating a runup of 10–12 m. In this article, we demonstrate that at the Shetland Islands between Norway and Scotland (Figure 1), this tsunami reached onshore heights at least 20 m above the sea level of that time.

We studied deposits from the tsunami event in both peat outcrops and in lakes. The tsunami eroded the peat surface and deposited a distinct and wide-spread sand layer that is recognizable in peat outcrops. Also, the tsunami inundated fresh water lakes, leaving a chaotic deposit of sand layers, rip-up clasts, re-deposited lake mud, and marine fossils.

A Sand Layer in Peat

In 1993, David Smith and others identified a distinctive sand layer in peat as much as about 6 m above high tide on the east shore of Sullom Voe [*Birnie et al.*, 1993; Figure 1, inset], and interpreted it as being a result of a tsunami. Radiocarbon dates of 1-cm slices of bulk peat at contacts above and below the layer indicated an age of ca 5500 ^{14}C yr BP, almost 2000 years younger than the Storegga tsunami event.

We examined coastal exposures around the entire Sullom Voe and found the same sand layer in better outcrops on the western side (site M, Figure 1). Here we could follow the sand layer more or less continuously from the shore, and up to 9.2 m above high tide level—a total distance of 150 m (Figure 2).

Close to the present shore, the tsunami deposit is 30–40 cm thick and shows large rip-up clasts of peat embedded in the sand (Figure 2). Many of the clasts are 10–30 cm in diameter with sharp edges. Also, pieces of wood and trunks were found in the sand. The sand, which is medium to very coarse, contains pebbles and cobbles; we even found a boulder as large as 25 cm in diameter (Figure 2).

The sand thins and fines inland; also, the erosion of peat decreases in this direction (Figure 2). Close to the sea, the sand is 30–40 cm thick. From about 18 m from the shore and inland, the sand thins from 10 cm to less than 1 cm at the maximum elevation (Figure 2). Between 0.8 and 4 m above high tide, the sand is normal graded, from very coarse sand with fine gravel particles at the bottom, to medium sand at the top. From 6 m above high tide and inland, the sand is massive—between 4 and 1 cm thick—and discontinuous, and it ends 9.2 m above high tide (Figure 2).

The sand layer has many of the characteristics from known tsunami deposits. The most commonly described tsunami deposit is a sheet of sand. Typically, it is normally graded and shows a decrease in thickness and grain size landwards [e.g., *Atwater and Moore*, 1992; *Dawson et al.*, 1988; *Bondevik et al.*, 1997b]. This trend is evident in this section. Eyewitnesses to many recent tsunamis have reported extensive erosion. The unconformity below the sand demonstrates major erosion.

Rip-up peat clasts, typical for the section between 0 and 6 m, make up a bed within the sand, with a distinct lower boundary (Figure 2). We interpret this as a result of at least two waves inundating the land. The first wave eroded the peat surface and transported rip-up clast of peat and sand. The backwash left the eroded clasts and other organic remains at the surface of the tsunami-laid sand. The following wave buried the clasts in sand. Storegga tsunami deposits inferred to show repeated waves are also known from coastal lakes in western Norway [*Bondevik et al.*, 1997b].

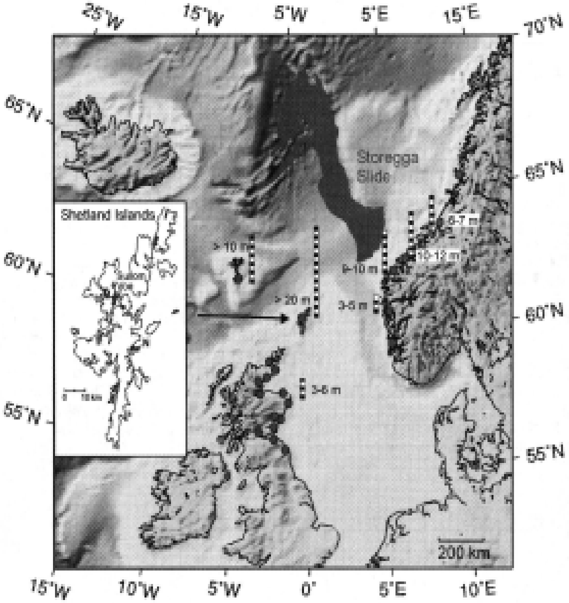


*Fig. 1. The Storegga slide off shore of Norway is one of the largest known Holocene slides on Earth. It triggered a large tsunami, dated to 7250–7350 ^{14}C yr BP, probably inundating most coastlines in the North Atlantic. Blue dots show where tsunami deposits have been mapped, and numbers show elevation of the deposits above the contemporaneous sea level [*Dawson et al., *1988; *Bondevik et al., *1997a; *Grauert et al., *2001]. Red dots on the inserted Shetland map show sites of tsunami deposits. M is the outcrop shown in Figure 2, and N is the site of the lake core in Figure 3. Original color image appears at back of volume.*

The Tsunami Deposits in Lakes

Coastal lakes have a high potential for preserving deposits from tsunamis. The deposits in four lakes close to present-day sea level on the north and eastern coast of Shetland (Figure 1, red dots outside Sullom Voe) show typical tsunami facies as documented from lakes on Norway's west coast [*Bondevik et al.*, 1997b]. These deposits have an erosive, sharp, lower boundary against the underlying lake mud (Figure 3). Coarse sand and fine gravel particles (2–6 mm) rest on this boundary. The sand often contains rip-up clasts of both gray silt and brown organic lake mud (Figure 3). Further up-core, the tsunami deposit is a mixture of plant fragments, twigs, bark, sand, and other re-deposited lake mud. The upper boundary is very gradual. In the sand, we have found marine diatoms, fragments of marine shells, and sea-urchins. This clearly demonstrates that material was brought into the fresh water lakes from the sea during the tsunami event.

Age and Height Estimation

Both in peat outcrops and in the lakes, we ^{14}C-dated the tsunami deposits using plant macrofossils. From the peat we obtained ages between 7120 ± 60 ^{14}C yr BP on seeds just below the sand layer, and 7025 ± 60 ^{14}C yr BP from a stick immediately above the sand layer. In the lake core (Figure 3), we dated a twig from within the tsunami deposit to 7320 ± 70. Leaves and seeds extracted from the lake mud just above the tsunami deposit are 7220 ± 70 ^{14}C yr BP. We conclude that the sand layer has the same age as the Storegga tsunami deposit dated in western Norway to ca 7300 ^{14}C yr BP [*Bondevik et al.*, 1997a]. The previous ^{14}C dates of bulk peat are 1500 to 2000 years too young most likely caused by penetrating roots. The roots transfer current atmospheric CO_2-carbon to deeper layers, thus reducing the ^{14}C age of the affected peat [*Nilsson et al.*, 2001].

Sea level at ca 7300 ^{14}C yr BP was much lower than today on Shetland. Marine deposits or other landforms associated with shore processes do not exist onshore, and the present beach often lies upon peat. Dated submerged peat [*Hoppe*, 1965] and a modeled sea level curve [*Lambeck*, 1993] suggest sea level at the time of the Storegga tsunami to be lower than -10 to -15 m. The tsunami deposits have been traced up to 9.2 m above high tide. This demonstrates a vertical run-up of around 20–25 m, a doubling of the previously known maximum run-up height for the Storegga tsunami.

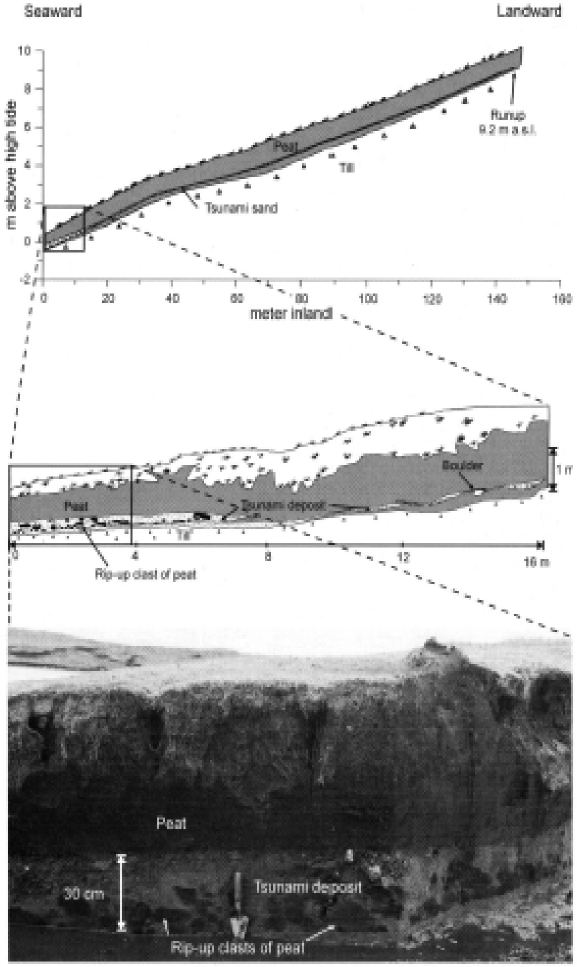


Fig. 2. The uppermost panel is a sketch of the tsunami layer in the entire 150-m-long outcrop (site M in Figure 1). The middle panel shows the first 16 m of the same outcrop. Between 0–6 m, large rip-up clasts of peat and pieces of wood embedded in the sand dominate the tsunami layer. Underneath the sand layer there is a profound erosional unconformity. Here the sand rests on till. From 9 m and inland, the sand is found in peat. Note that the sand layer thickens in the small depressions in the peat. At ca 14 m, a boulder is present within the tsunami layer. The photo shows the first 4 m of the outcrop. Original color image appears at back of volume.

Acknowledgments

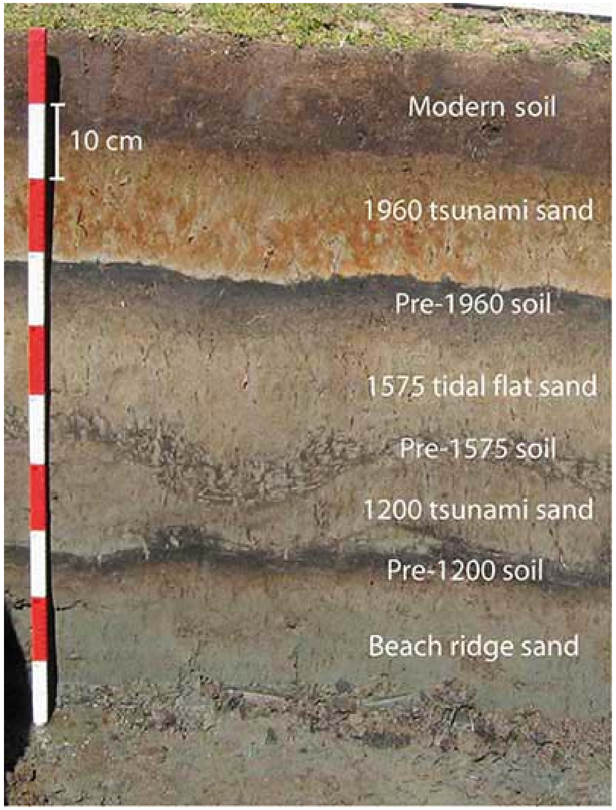
Brian F. Atwater reviewed the manuscript and suggested several changes that improved the paper. Norsk Hydro is acknowledged for supporting the fieldwork and other laboratory activities. Gudrun Skjerdal carefully picked seeds and insect remains from the peat for AMS radiocarbon dating. The ^{14}C dates were obtained at the Radiocarbon Laboratory in

---

By Stein Bondevik, Jan Mangerud, Sue Dawson, Alastair Dawson, and Øystein Lohne

Wave–sea bed interaction

- Damping: decrease of wave height
- Sediment transport

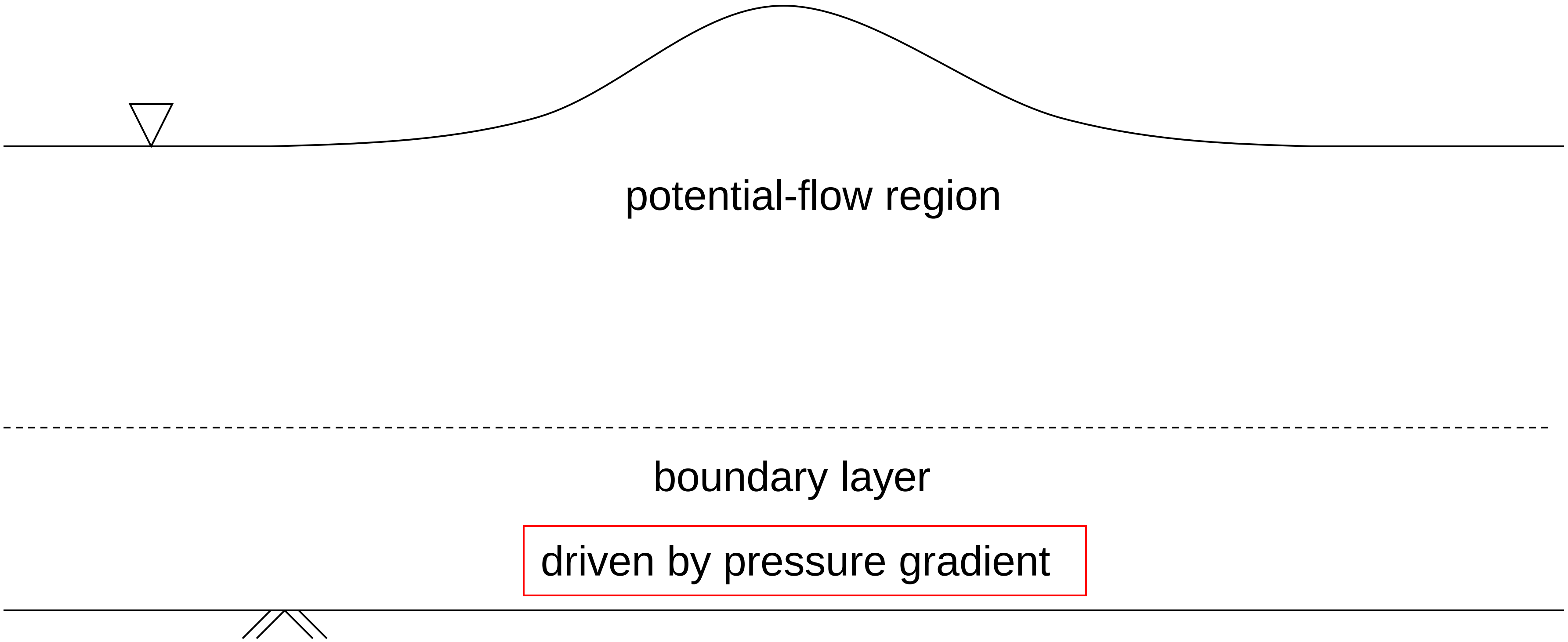


Soil profile from Maulin, Chile (http://www.ga.gov.au/ausgeonews/ausgeonews200609/echoes.jsp)

Topics in fluid-mud problems

water	**interface**	**fluid-mud**
wave attenuation	wave-induced motion	rheology (viscous, viscoelastic, viscoplastic, plastic, elastic, …)
velocity field	breaking	wave-induced flow
		transport of fluid-mud

Boundary layer flow under solitary waves

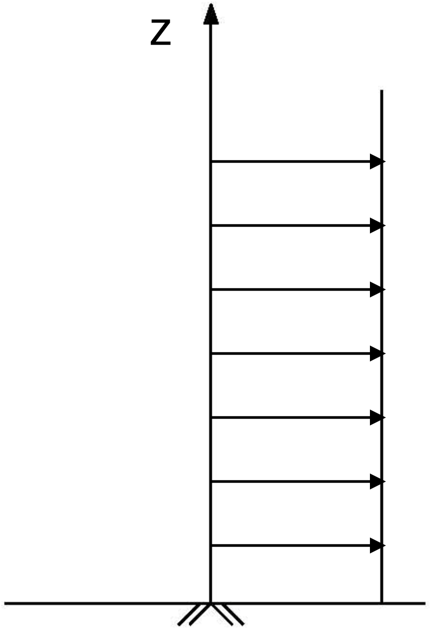


potential-flow region

boundary layer

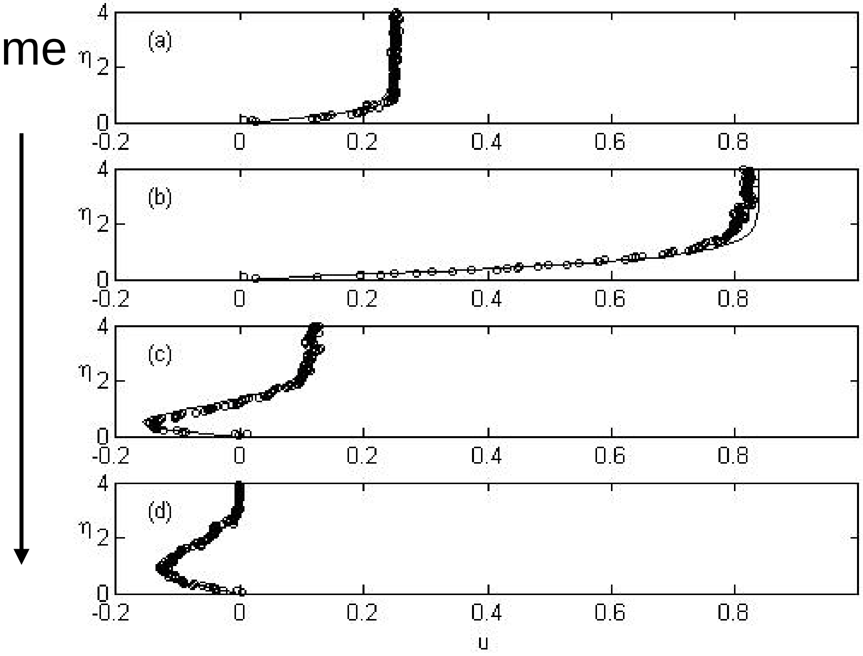
driven by pressure gradient

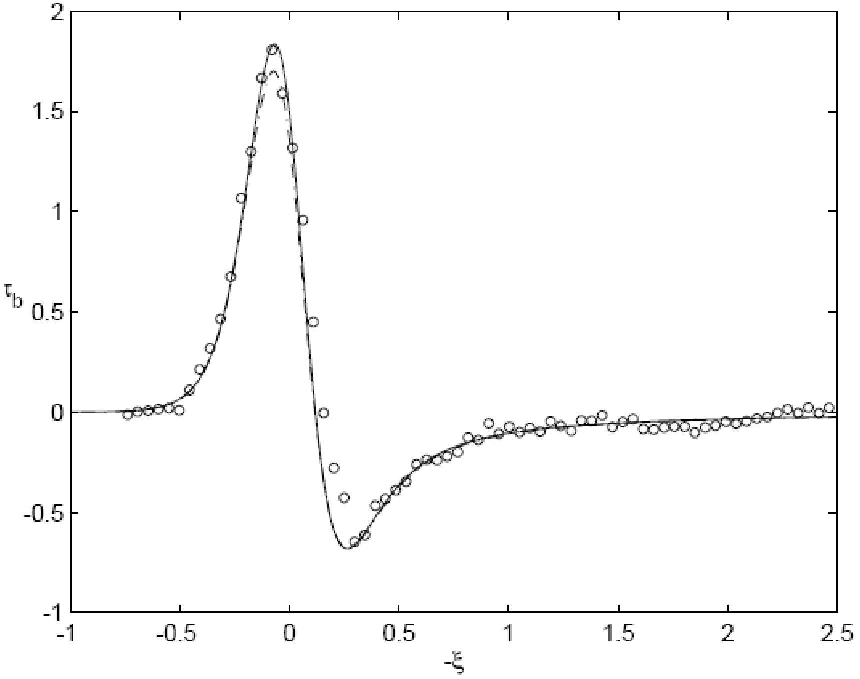
Bottom boundary layer analysis



irrotational
component

Flow reversal

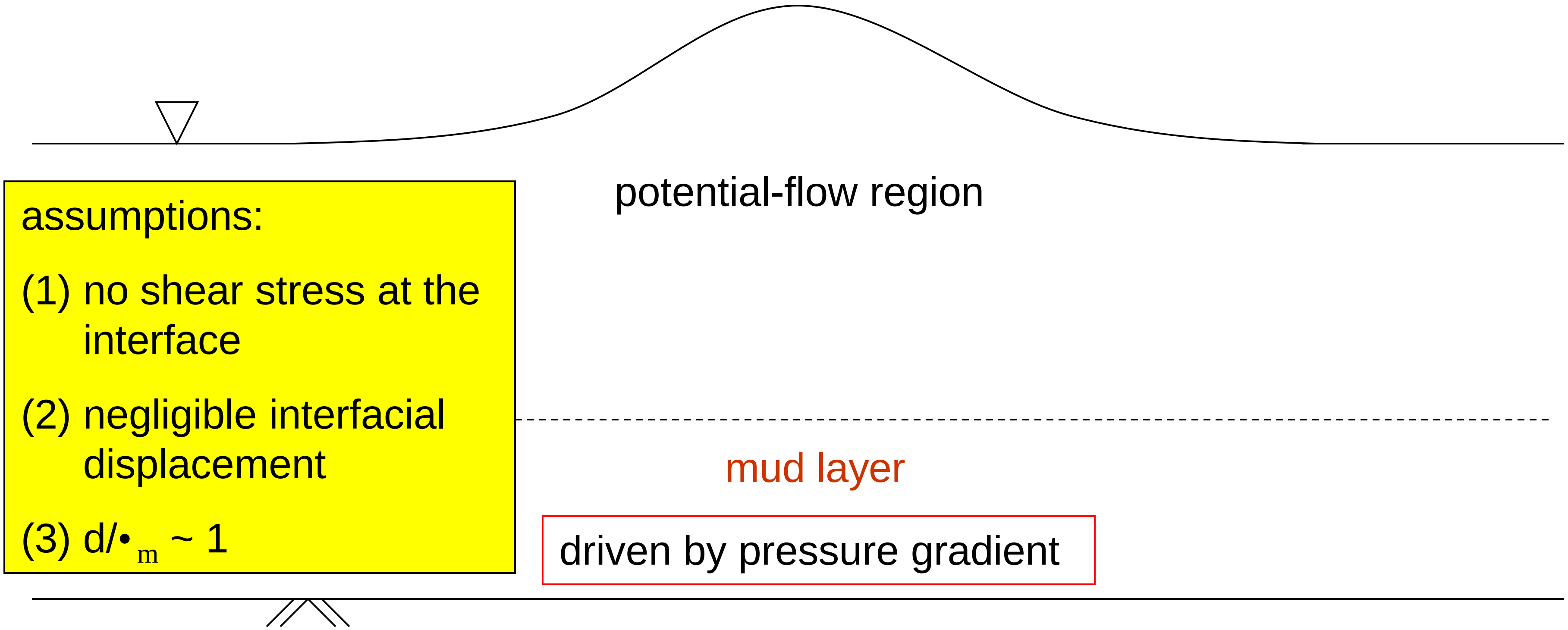

time



Vertical profile of **horizontal velocity**
(Liu & Park 2008, COE)

Time history of **bed shear stress**
(Liu, Park & Cowen 2007, JFM)

Wave-induced flows in a muddy seabed



potential-flow region

mud layer

driven by pressure gradient

assumptions:

(1) no shear stress at the interface

(2) negligible interfacial displacement

(3) $d/\delta_m \sim 1$

$$\frac{d'}{\delta'_m} = \frac{\text{mud layer thickness}}{\text{boundary layer thickness}}$$

Experimental setup (1)

Y. S. Park, P. L.-F. Liu and S. J. Clark

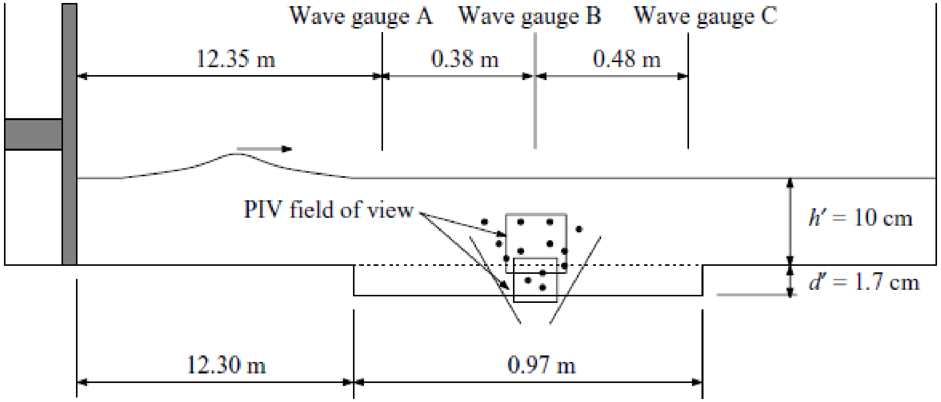


FIGURE 1. Experimental set-up (not to scale).

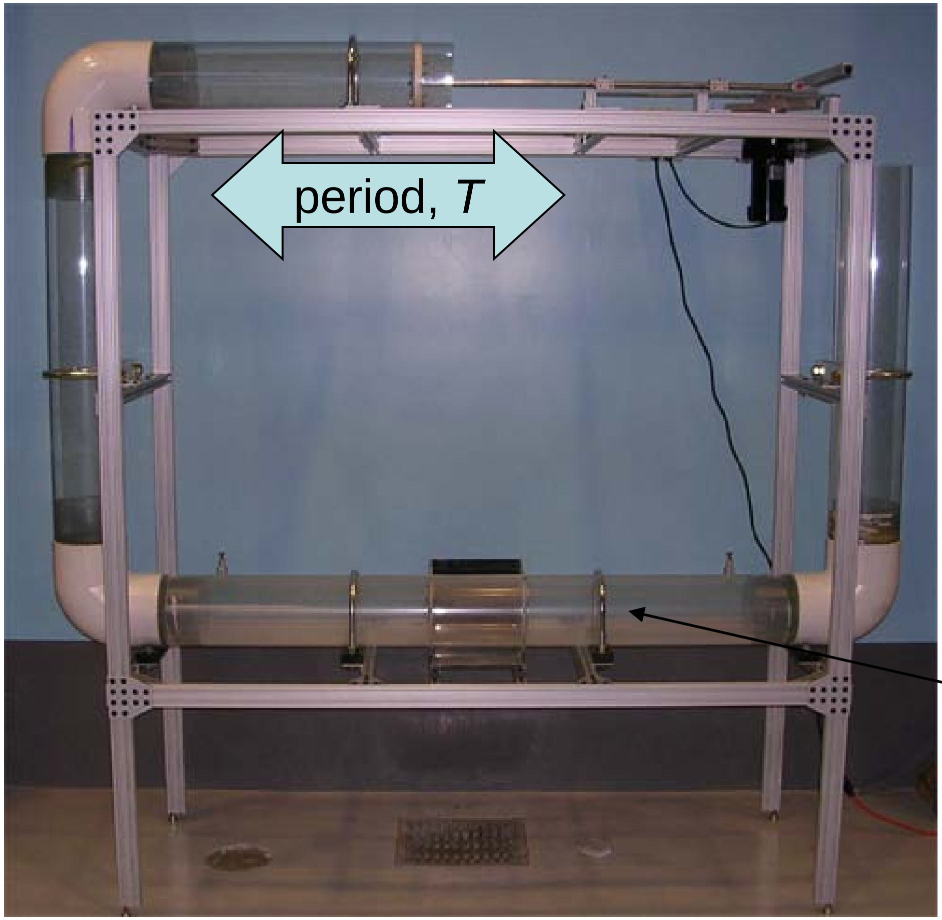
Experimental setup (2)

justifications:

(1) driven by pressure gradient.

(2) no-slip condition on the wall.

(3) no-shear-stress condition at the center.

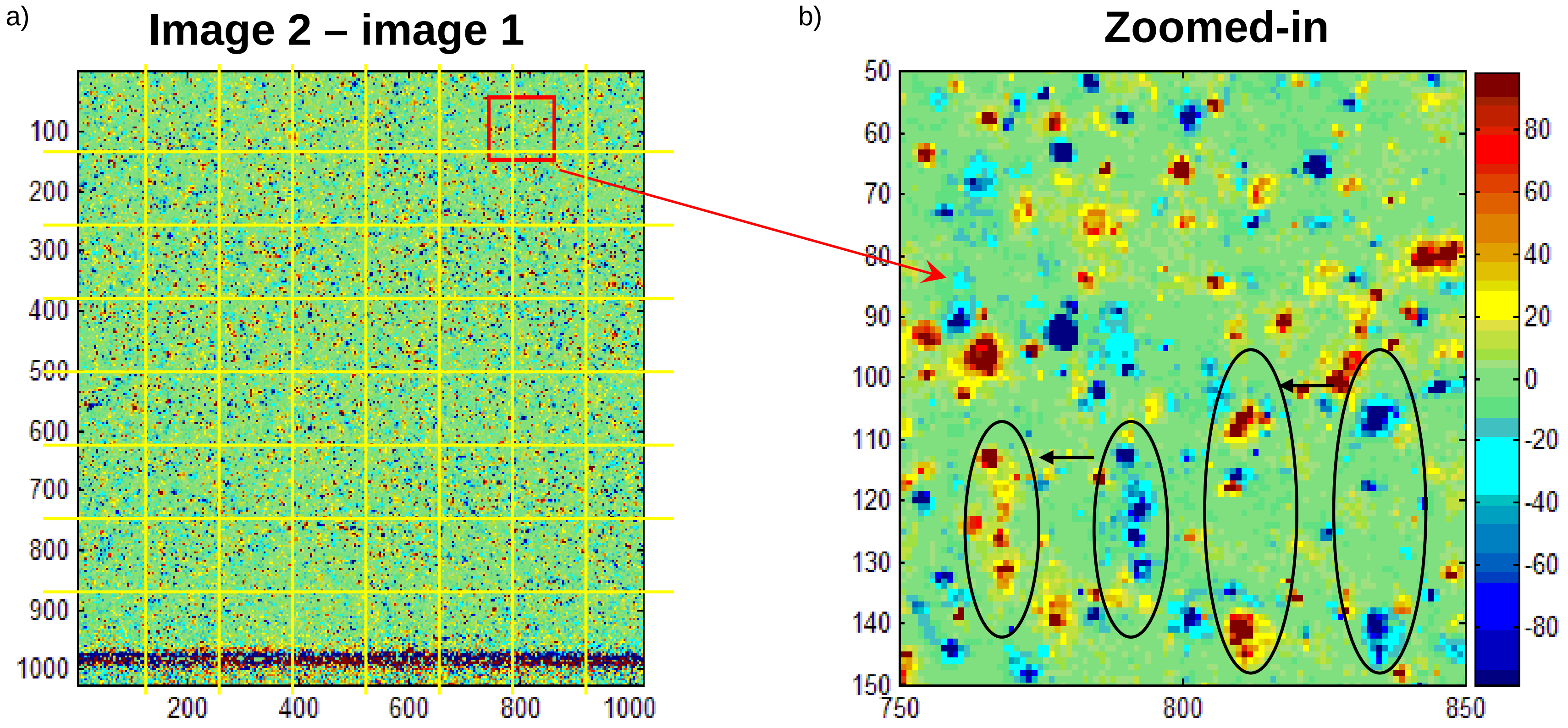


radius, $R = d$

boundary-layer thickness, $\delta = \sqrt{\nu T}$

PIV analysis

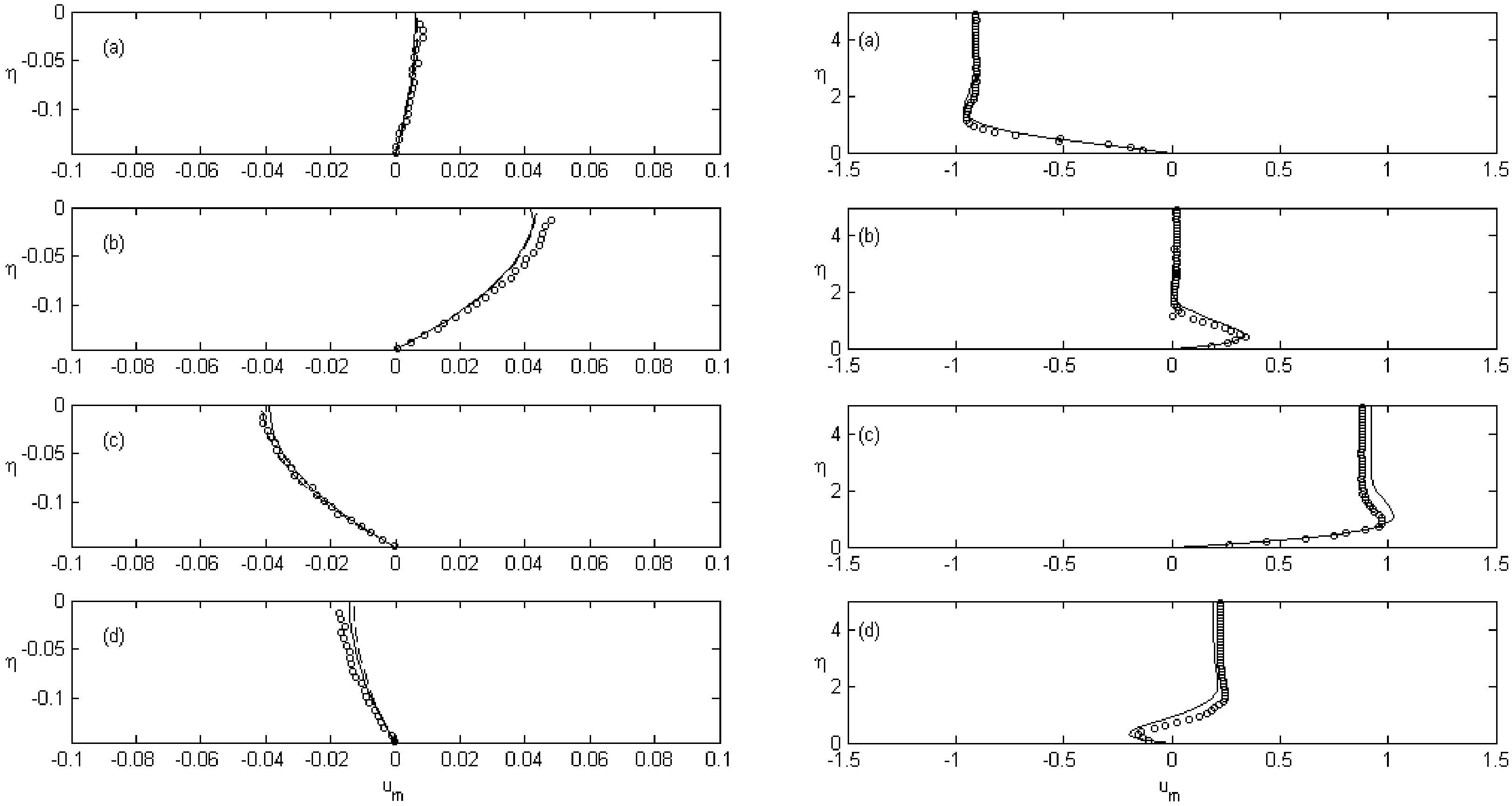
Difference b/w two images of a pair



a) Image 2 – image 1

b) Zoomed-in

Verification with a Newtonian fluid

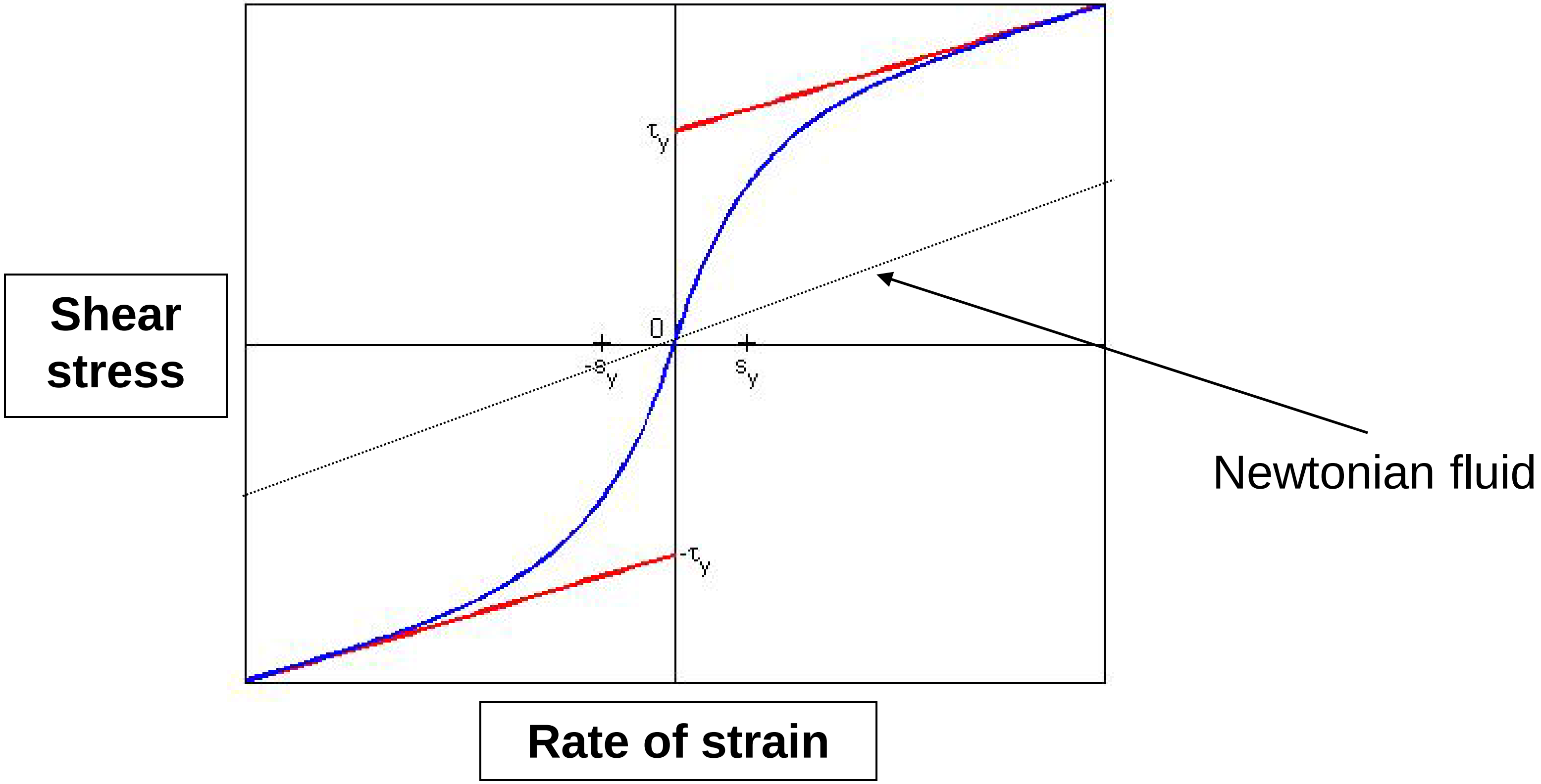


$\delta > d$

$\delta \le d$

Vertical profile of **horizontal velocity**
(Park, Liu & Clark 2008, JFM)

Material with yield-stress



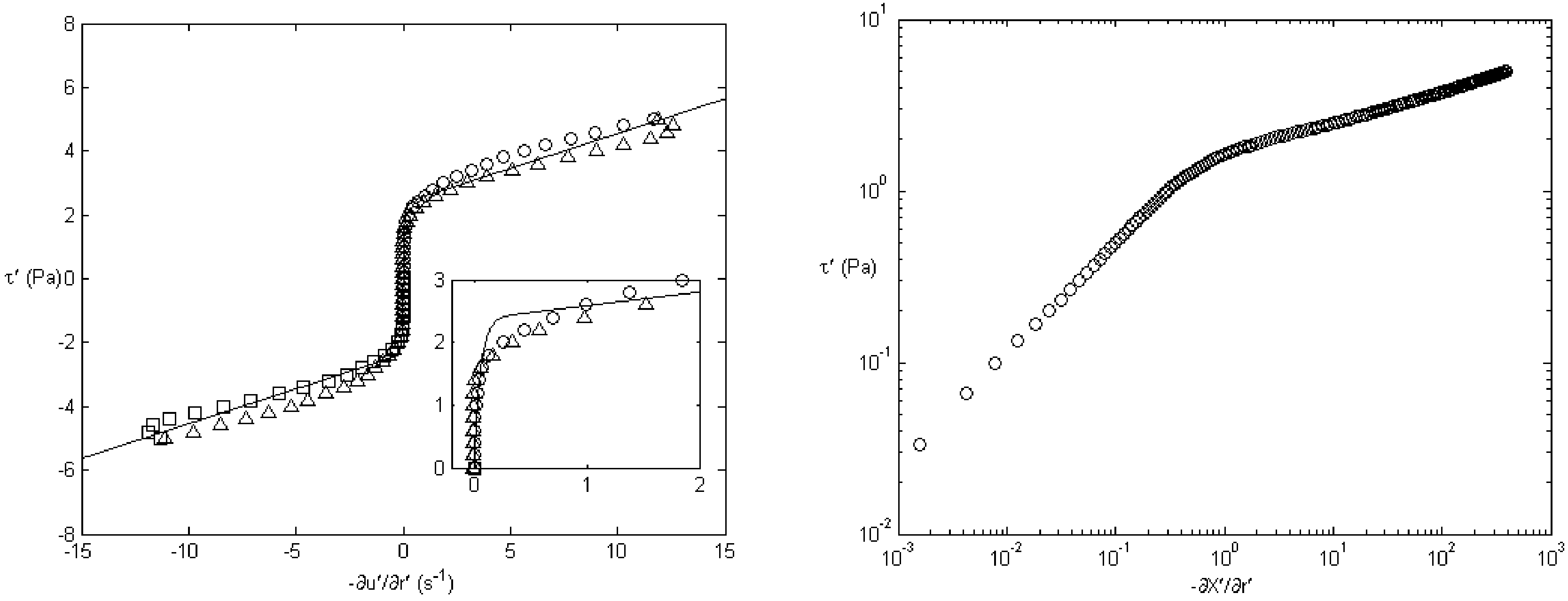
Shear stress

Rate of strain

Newtonian fluid

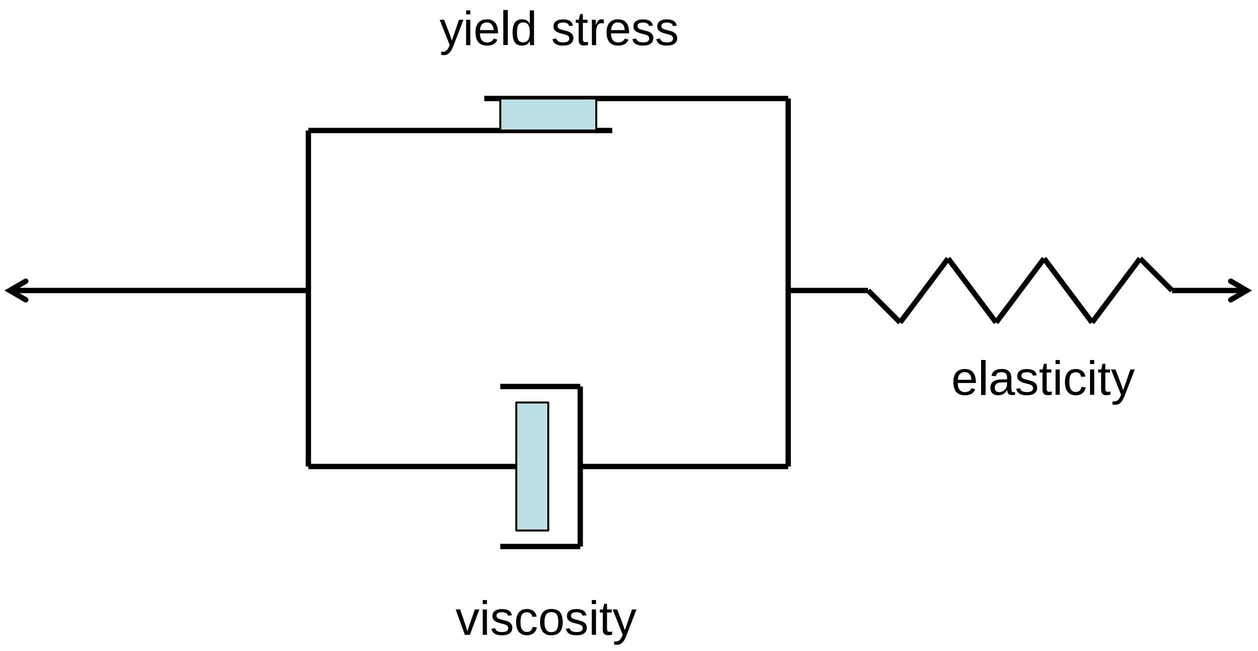
red: the Bingham model, **blue:** the Papanastasiou model

Carbopol: a clear, viscoplastic mud

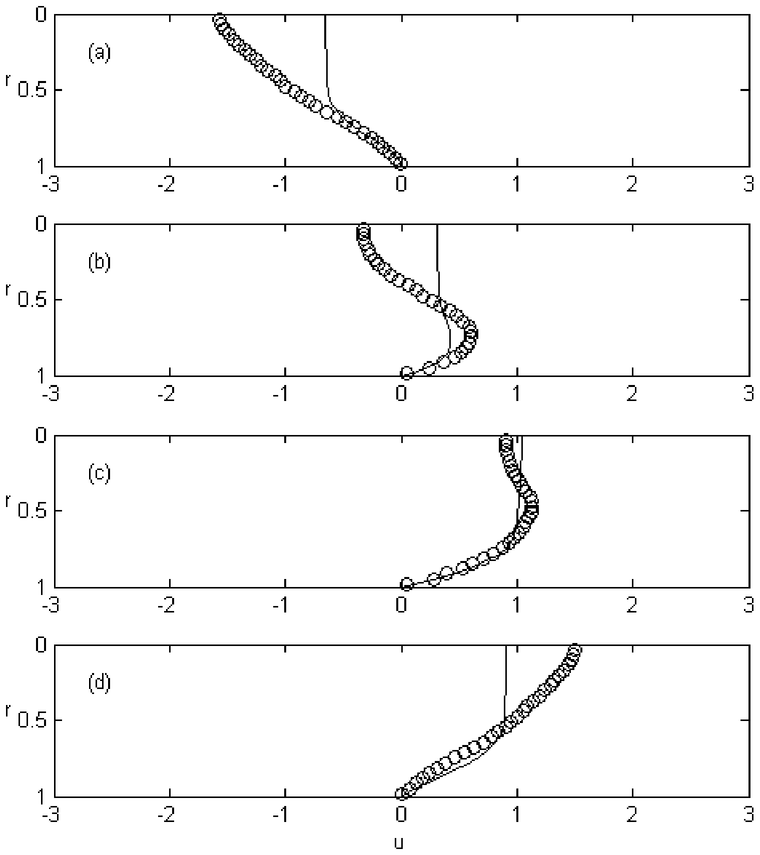


A steady-shear rheological measurement of aqueous solution of Carbopol (0.075 wt%, pH 7.0) and a fitted regularized viscoplastic model.

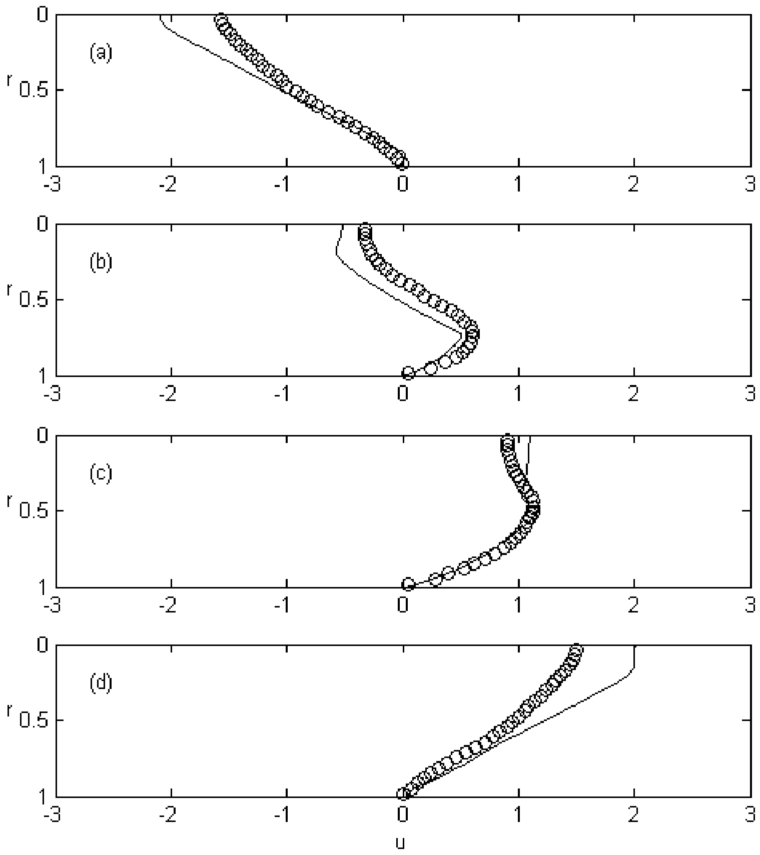
An elasto-viscoplastic model



Numerical simulation



Bingham model



elasto-viscoplastic model

An important observation

- A simpler viscoelastic model can also fit the experimental data (Park 2009).
- However, different rheological parameters must be used for different cases with the same material.
- The suggested model works with **constant** rheological parameters for different cases.

Toward real mud

- No simple model (viscous, viscoplastic, viscoelastic, and elastic) fully describes real mud.
- Mud is known to change rheological properties according to external forcing.
- That may be because we are not using the correct rheology.
- Plus, natural fluid-mud is stratified.

U-tube at Dundee

Thank you!!!