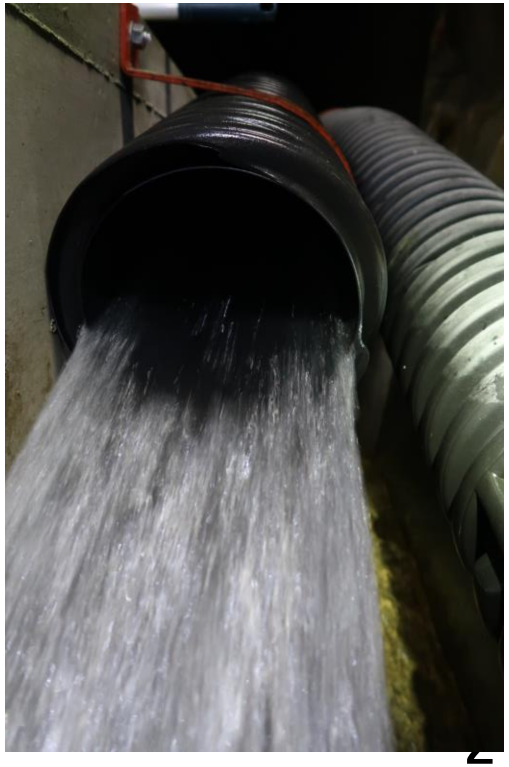
Estimating the Newtonian noise of groundwater at the KAGRA

Dec/1、Face to Face, Poster(slide style)

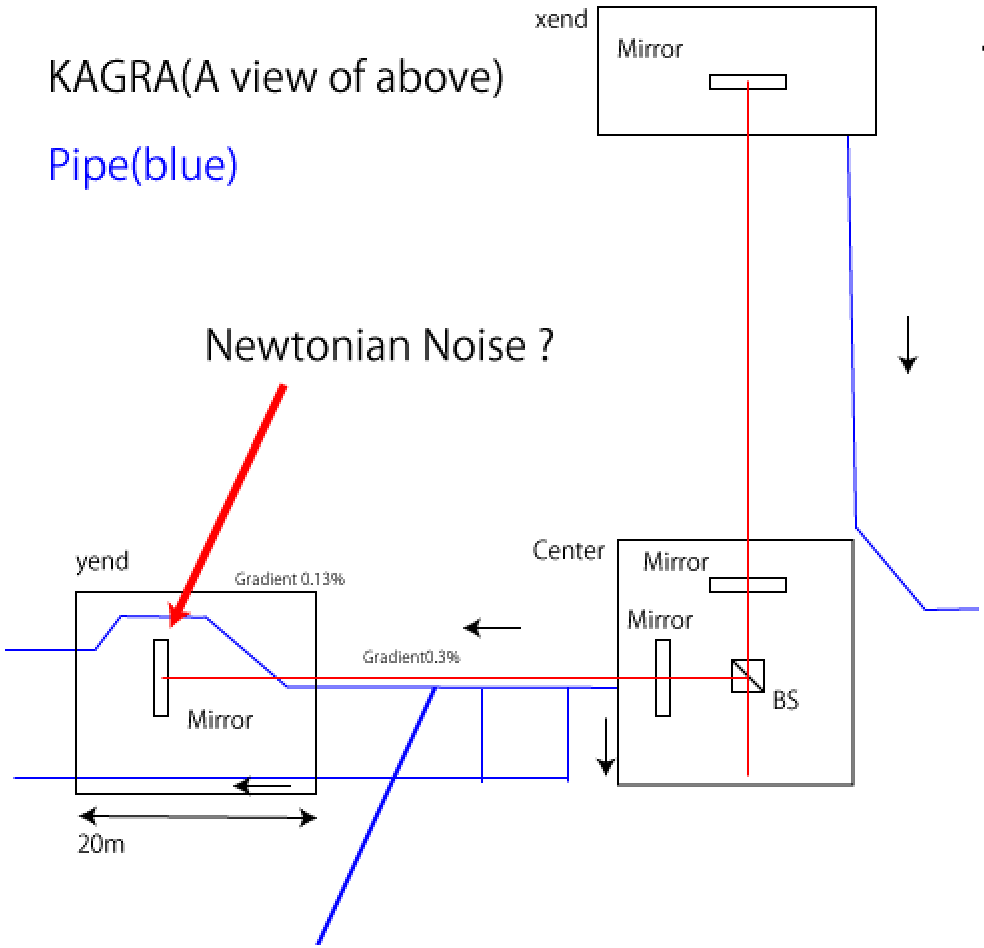
Takanori Suzuki(Tokyo Institute of Technology)・Kentaro Somiya (Tokyo Institute of Technology)
・Tatsuki Washimi(NAOJ)・Takaaki Yokozawa(ICRR)・Atsushi Nishizawa(RESCEU)

Background

- The gravitational wave telescope KAGRA is built 300m underground to reduce ground vibrations.
- Groundwater is flowing through pipes near the KAGRA mirror, therefore Newtonian noise generated by Groundwater can be an issue.

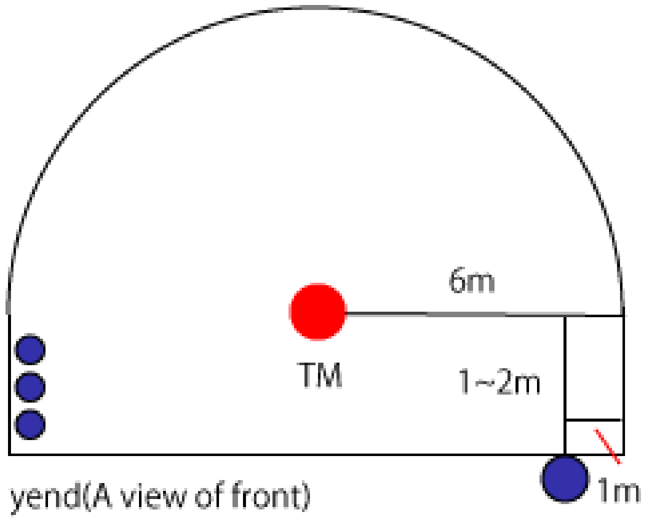


Pipe position



A view of KAGRA from above.

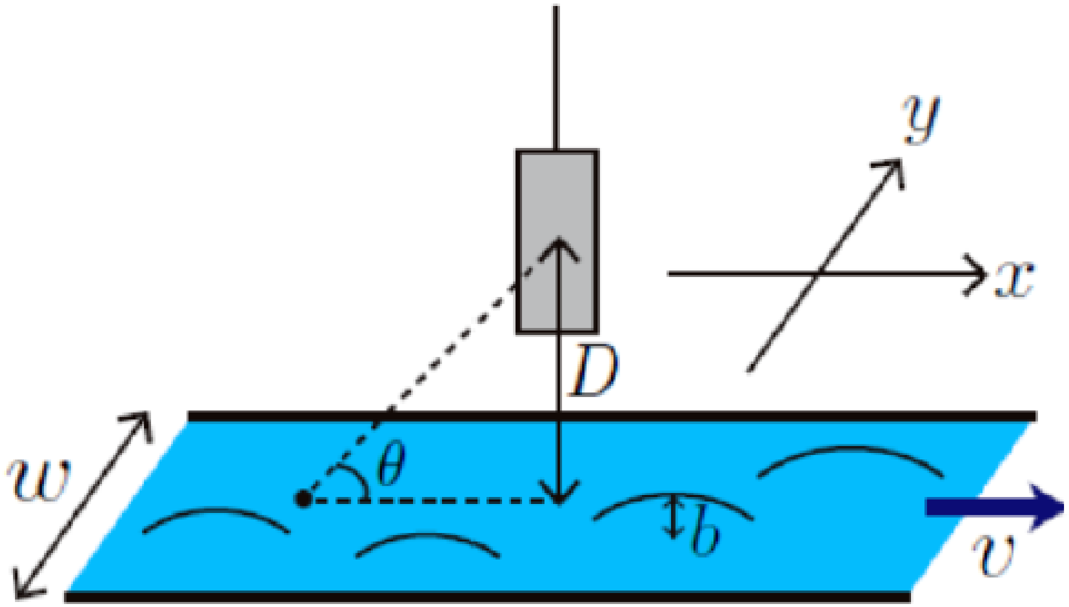
The pipe and the test mass are close at Y-end.
The distance between the mirror and the pipe is 1-2m in the z(vertical) direction,
5m in the Horizontal direction



A view of Y-end from front.

Formulation of water Newtonian noise

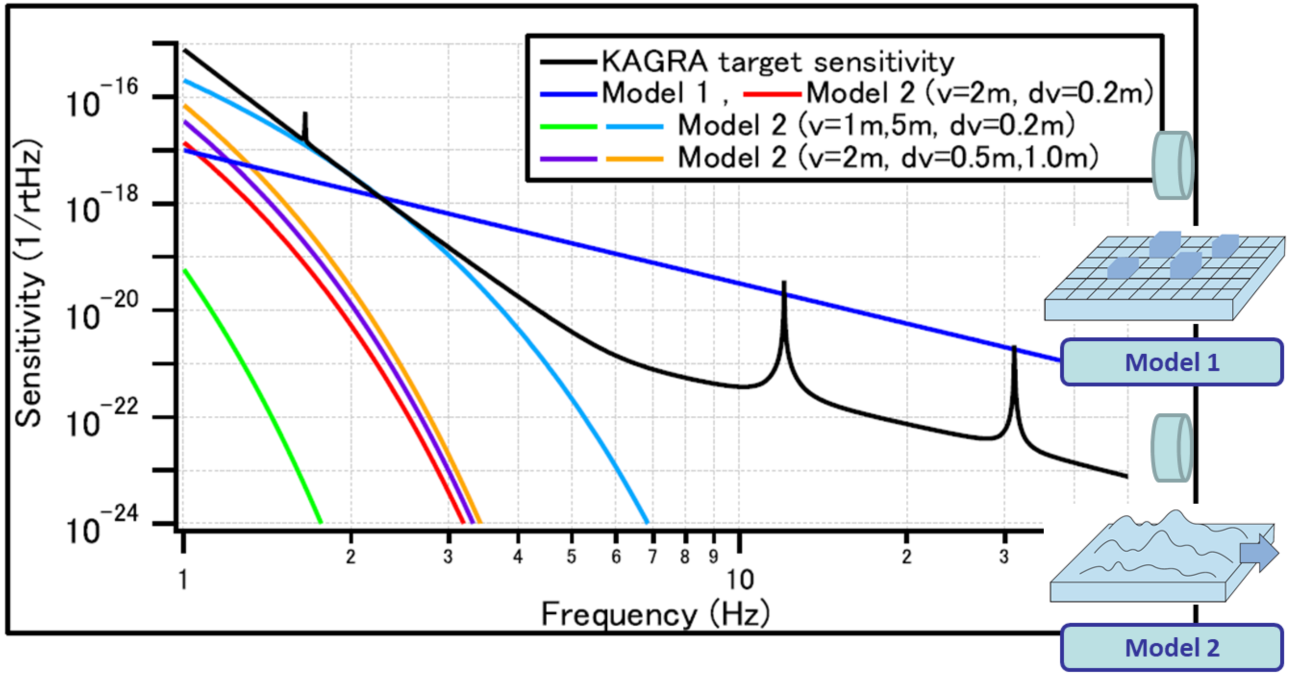
Fluctuation of water surface generate fluctuation of local gravitation.



$$a = \int\int \frac{G\rho b(x,y,t)\cos\theta}{(x-x_{TM})^2+(y-y_{TM})^2+(z-z_{TM})^2} dxdy$$
$$= G\rho \int\int \frac{b(x,y,t)\cdot(x-x_{TM})}{((x-x_{TM})^2+(y-y_{TM})^2+(z-z_{TM})^2)^{3/2}} dxdy$$

⇨ The fluctuation of the water surface (b(x, t)) get from simulation data.

Theoretical model(Nishizawa-chen model)



Model1 : The water surface is fluctuating at each point

Model2 : Waves formed on the surface of the water move in keeping shape

⇧

This result is a prediction assuming a certain water surface motion model. There is no guarantee that water surface motion will be a reality.

Realistic simulation for water Newtonian

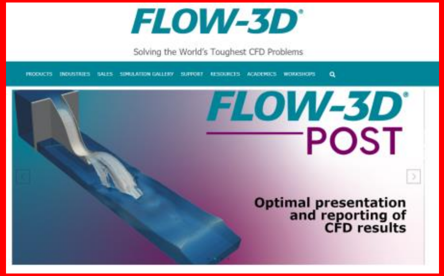
NN calculation

$$a(t) = \iint \frac{G\rho z(x,y,t)\cos\theta}{D^2 + x^2 + y^2} \mathrm{d}x\mathrm{d}y$$

$$h(t) = \frac{1}{L} \iint a(t)\mathrm{d}^2 t$$

water level $z(x,y,t)$ [m] data

Water fluid simulation



water current $J(t)$ $[\mathrm{m}^3/\mathrm{s}]$

Water fluid monitor

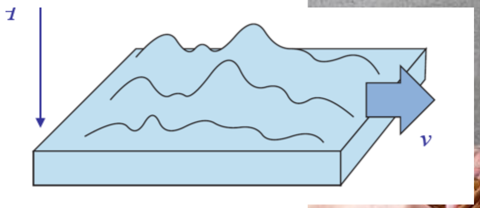
Me

Theory don't suppose exact wave shape, so we have to know wave detail(purpose).

Geometry

KAGRA Geometry

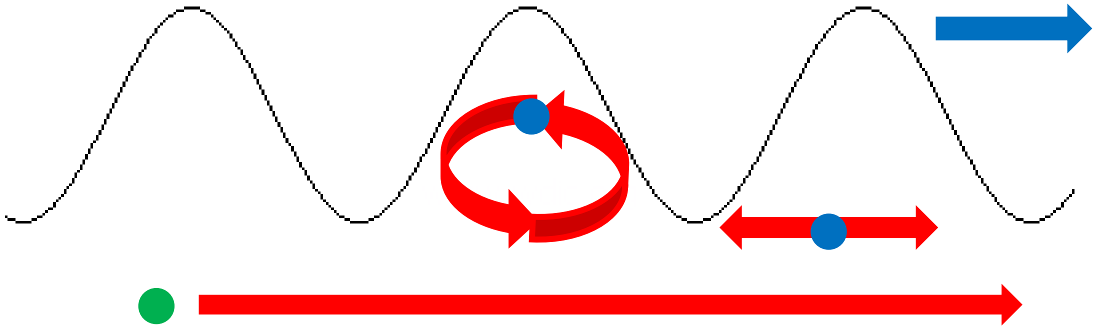
Explanation of technical terms



Super critical flow
射流

Sub critical flow
常流

Flow and Wave concept



The flow has a velocity(v_f) in the medium itself

Waves is transmitted through the medium with a velocity (v_w)

Super critical flow: $v_f > v_w$
Sub critical flow: $v_f < v_w$
Hydraulic Jump: boundary

Depth: Super<Sub critical flow

Hydraulic jump

- Hydraulic jump is white wave point.
- Hydraulic jump is the sudden rise in water level that occurs when Super critical flow becomes Sub critical flow.

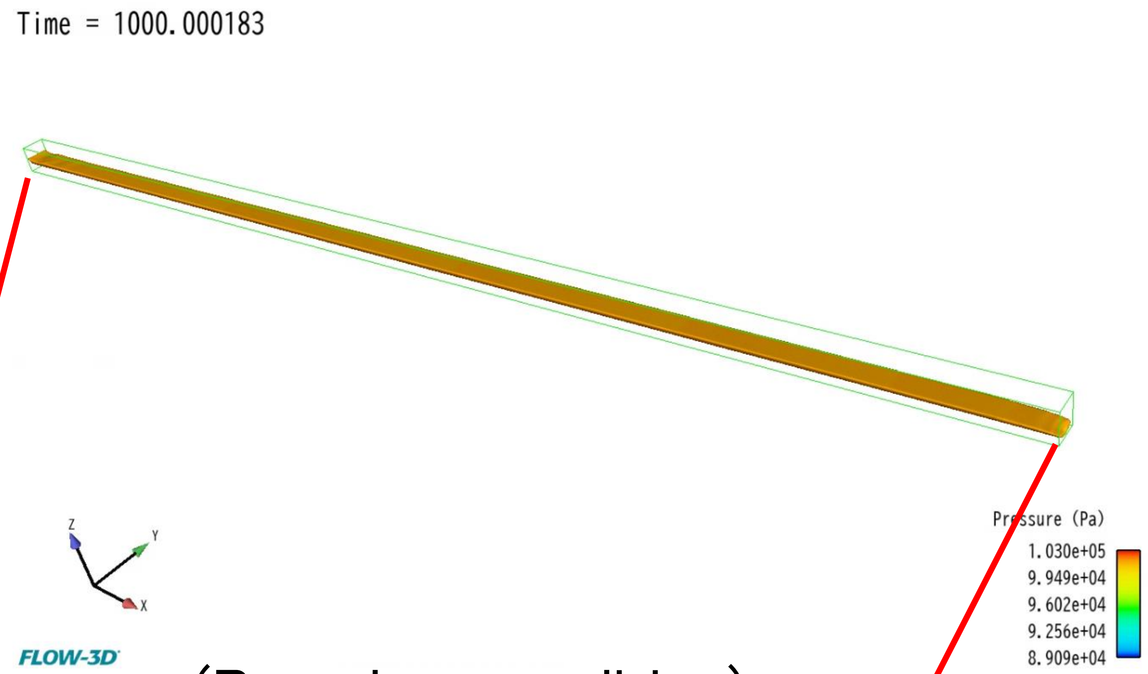
Super critical flow

Sub critical flow

Hydraulic jump

Water simulation

● Pipe condition

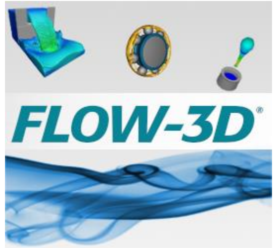


Inject water (Boundary condition)

Out flow(Boundary condition)

・We designed and simulated a straight pipe as shown on the left.

Pipe Length: 20m
Radius: 0.2m
Roughness height: 0.1～3.2mm
Gradient: 0.3%
Boundary condition:36.2～181 t/h
(=(0.1～0.5)$\times 0.2^2 \times \pi$ m^2 $\times$0.8 m/s)



We Used flow-3D

[Flow Science Japan - Excellence In Flow Modeling (flow3d.co.jp)](flow3d.co.jp)

Simulation Conditions

Flow rate(t/h)	Roughness height(mm)	Simulation time(s)
36.2	3.2	1010
72.4	3.2	1010
109	3.2	1010
145	3.2	1010
181	3.2	1010
109	0.1	1010
109	0.4	1010
109	1.2	1010
109	2.0	1010

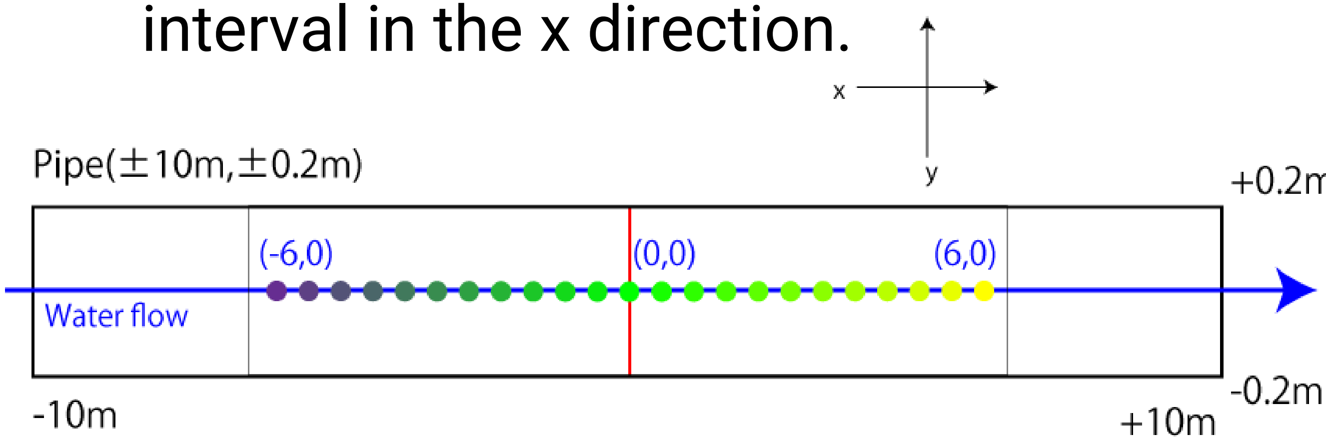
・Flow rate is the constant amount of water flowing into a pipe.
・Roughness height simply corresponds to the unevenness the pipe surface.
We did a flow rate comparison and a Roughness height comparison.

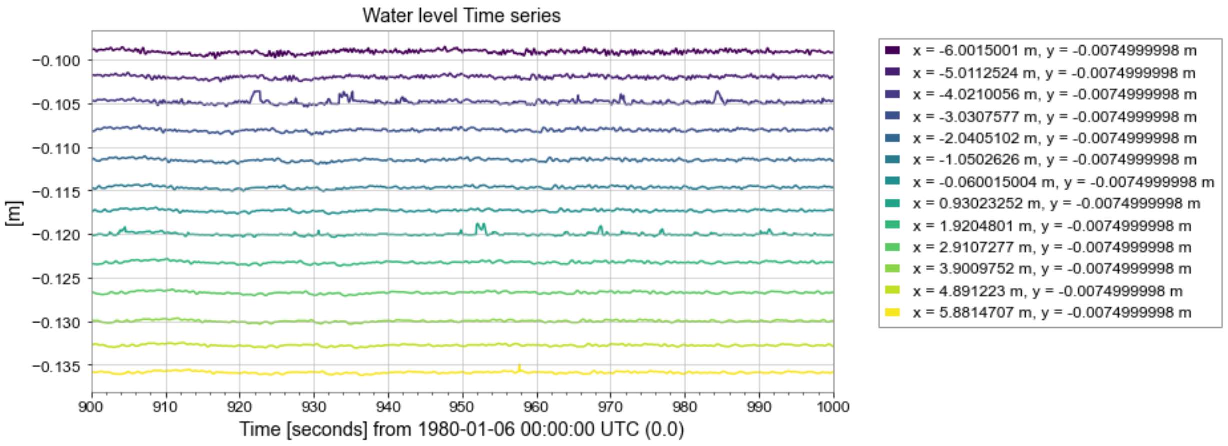
State of water

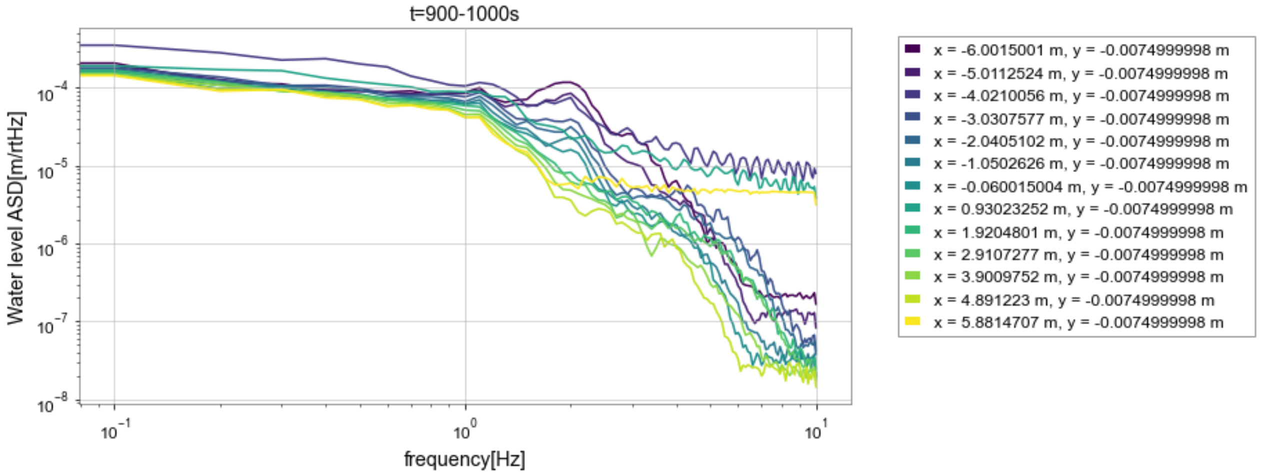
- Water level(Flow depth)

Water depth increases as it goes downstream.
This is the result of 36.2 t/h.
The same trend holds for the other conditions.

Water depth timeseries by 0.5m interval in the x direction.



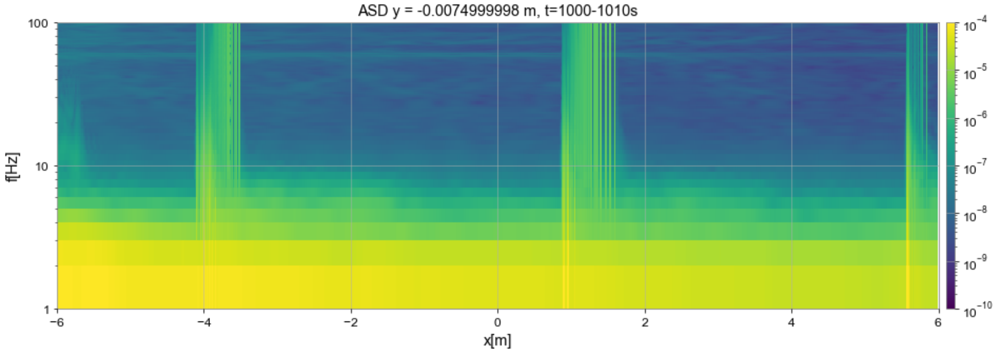




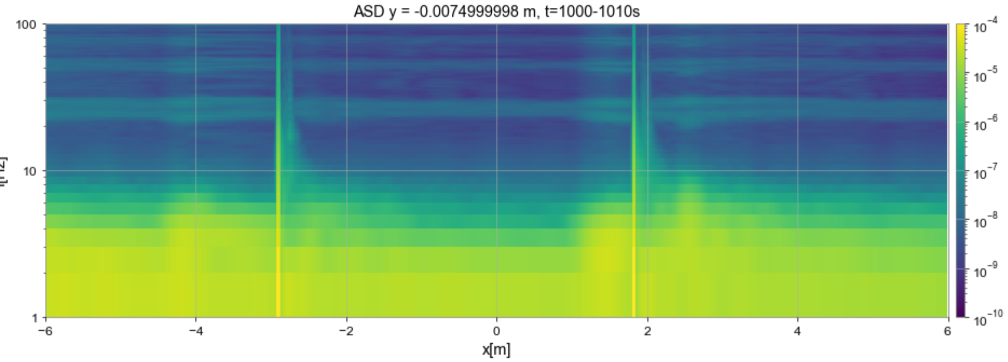
Fluctuations in the high frequency range are large at several points.

State of water(Flow rate)

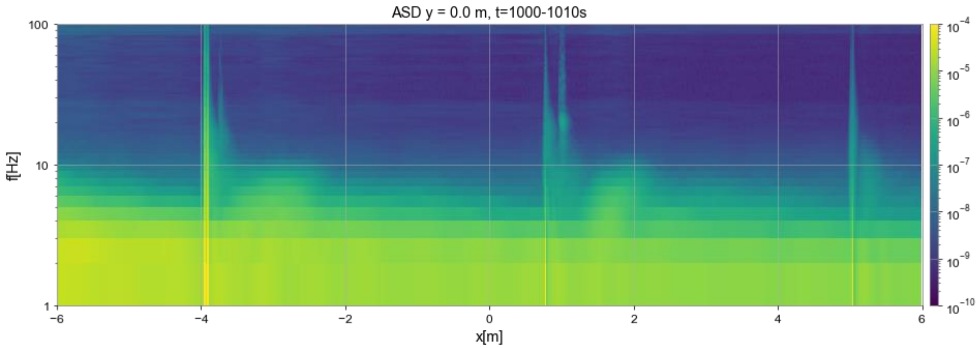
- ASD(-6～6m,y=0,1-100Hz)



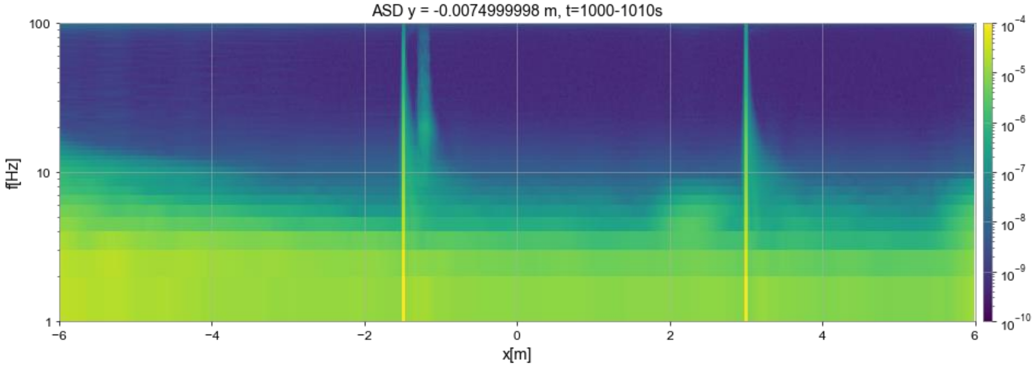
36.2t/h



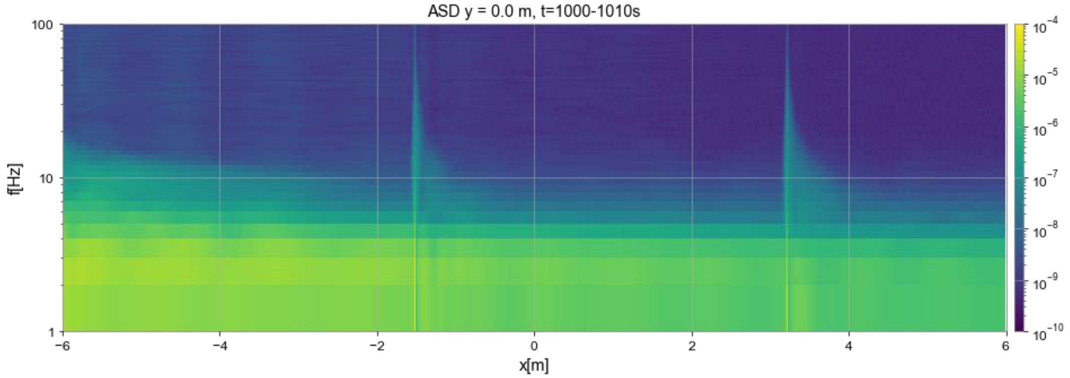
72.4t/h



109t/h



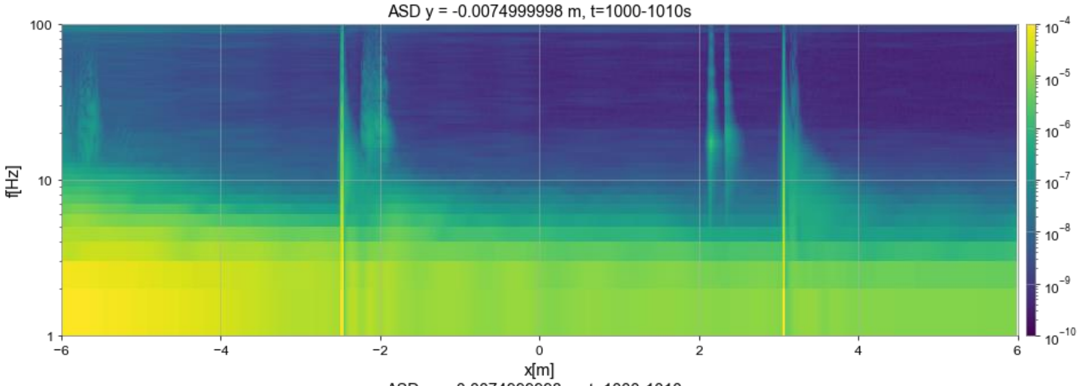
145t/h



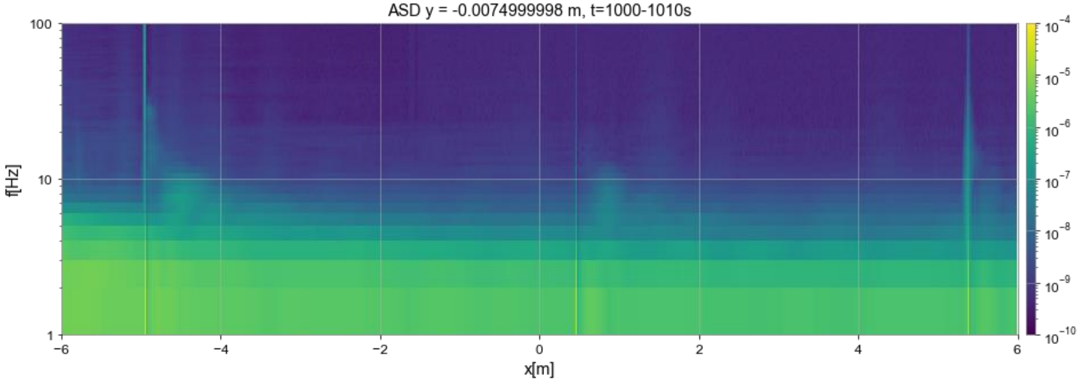
181t/h

State of water(Roughness height)

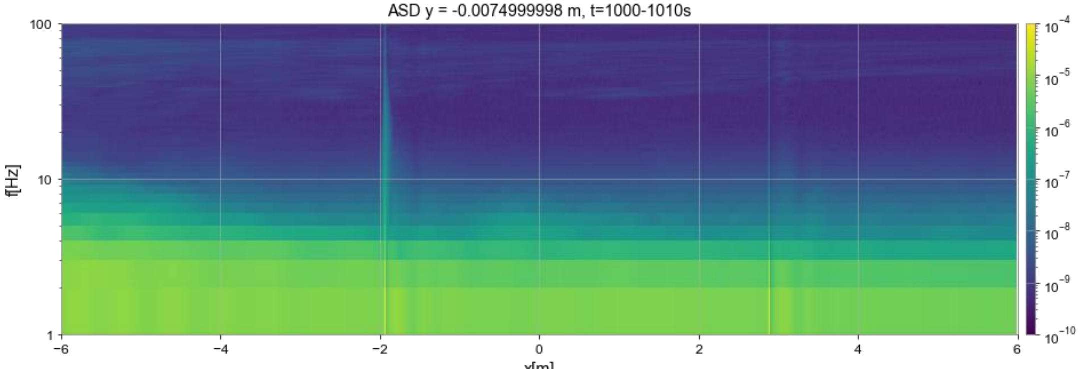
- ASD(-6～6m,y=0,1-100Hz)



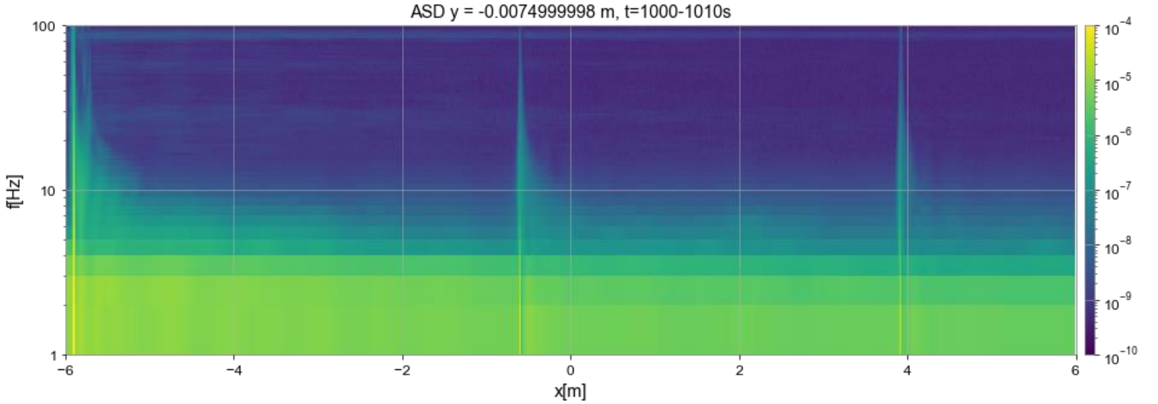
K=0.1mm



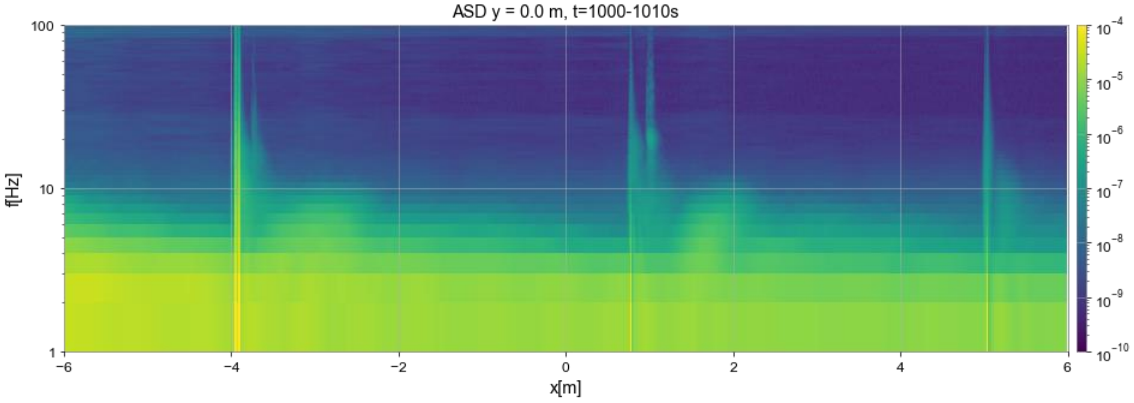
0.4mm



1.2mm



2.0mm



3.2mm

Discussion about the state of water

Tokyo Tech

- Below 10 Hz, it is necessary to consider the fluctuations of the entire water surface when considering Newtonian noise.
- Above 10 Hz, the influence of fluctuations at several points is significant.
  We consider that Hydraulic jump are occurring at those points.
- The number of Hydraulic jumps depends on conditions(flow rate, Roughness height).

Calculation of Newtonian noise

- Integrate gravitation(by water mass)

$$a = \iint \frac{G\rho b(x,y,t)\cos\theta}{(x-x_{TM})^2+(y-y_{TM})^2+(z-z_{TM})^2}dxdy$$
$$= G\rho \iint \frac{b(x,y,t)\cdot(x-x_{TM})}{((x-x_{TM})^2+(y-y_{TM})^2+(z-z_{TM})^2)^{3/2}}dxdy$$

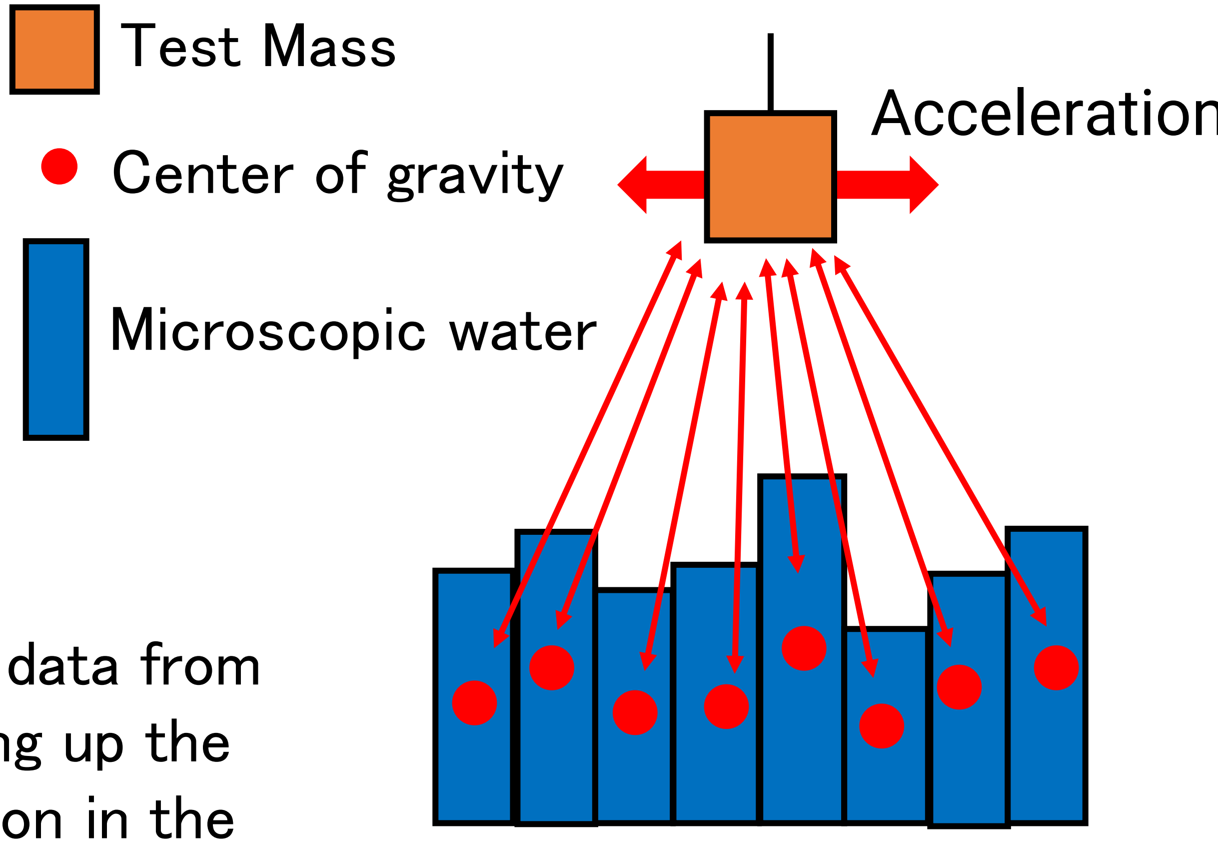
Microscopic water

・Center of gravity : x, y , z(water half level)

・Mass : $\rho \times b \times dx \times dy$

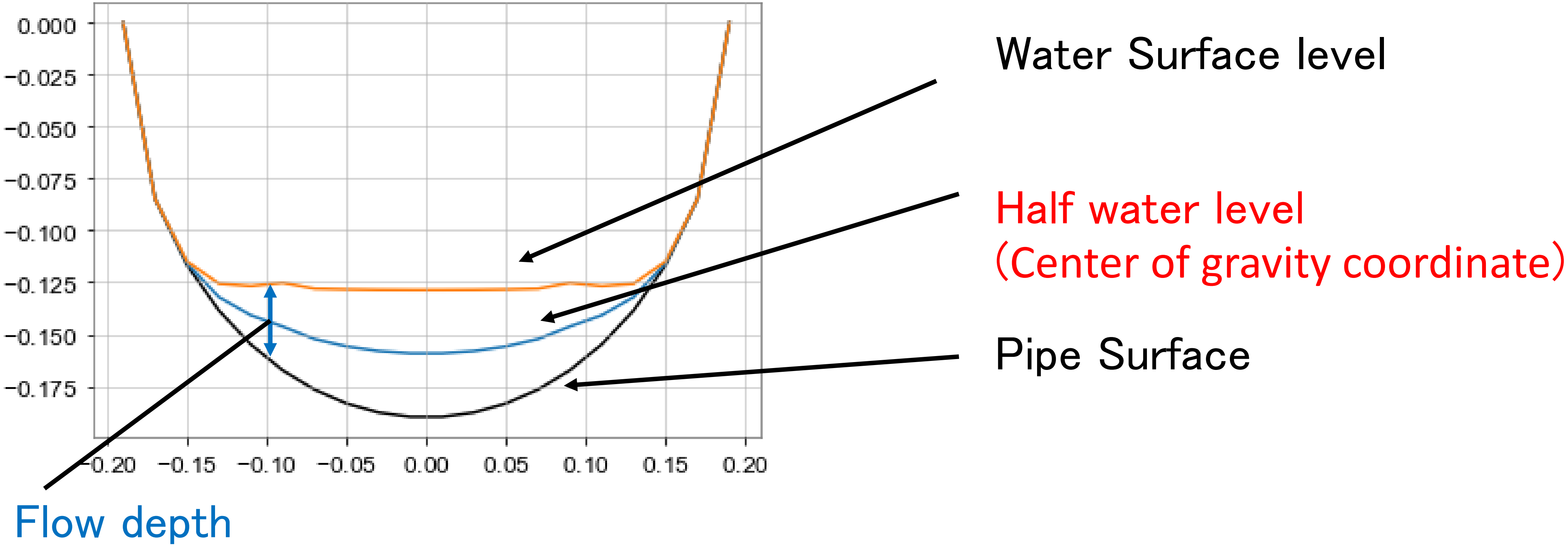
・Test mass : (x_{TM}, y_{TM}, z_{TM})=(0m, 5m, 1.5m)

・We wrote a program in python to analyze the data from the simulation. The noise is calculated by adding up the universal gravitational forces due to the variation in the mass of each water.



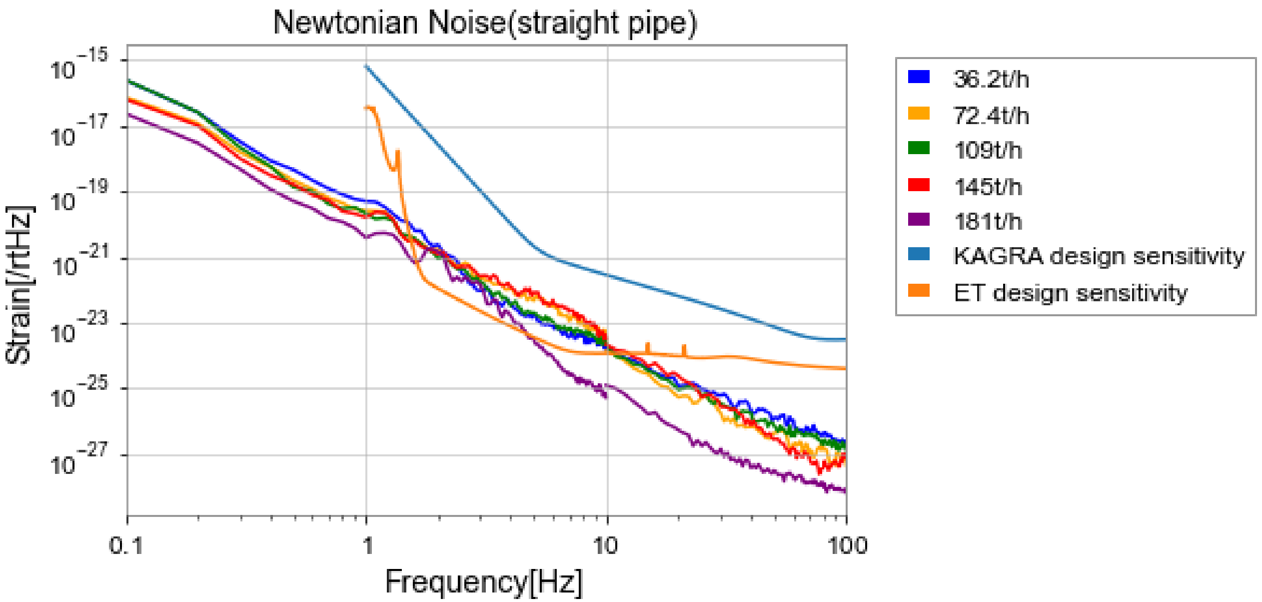
Calculation of Newtonian noise

- Coordinate setting(Mirror mass, Water mass)



Newtonian noise

- Comparison of differences in initial flow rates



(0.1Hz–10Hz: 900s–1000s
10Hz–100Hz: 1000s–1010s,)

・Integrate x=−6 m～6 m, y=−0.2 m～0.2 m area gravitation by water mass.

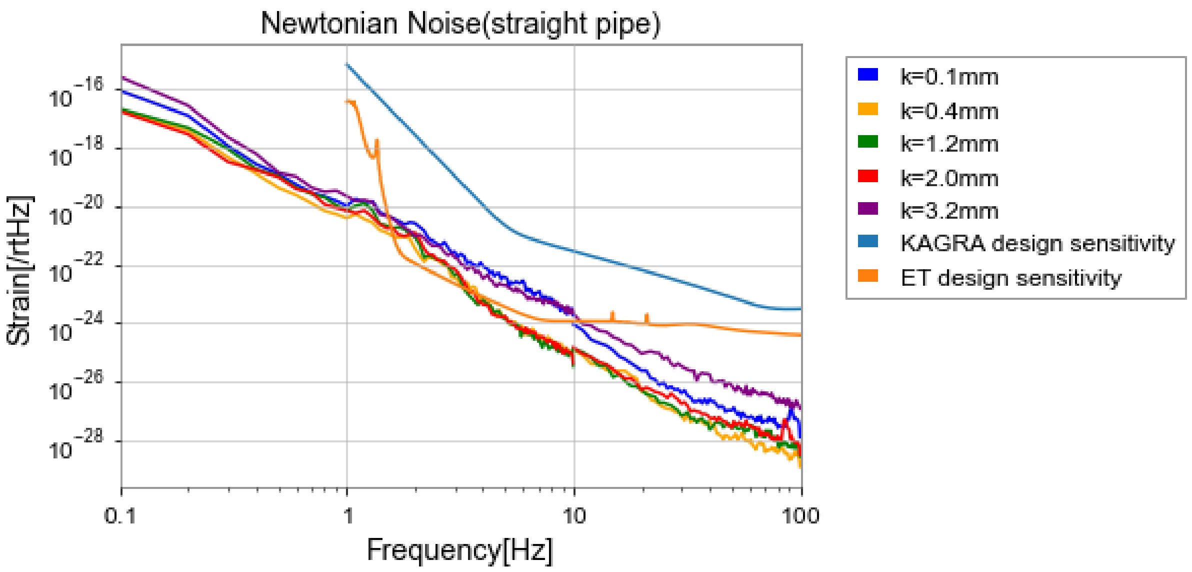
・Noise is f^{-4} to f^{-3} in 1 Hz–10 Hz, and f^{-3} in 10Hz–100Hz.

・ At lower frequencies , the noise level is higher.

・181 t/h is the least noisy condition up to 100 Hz. However, lower flow rates do not imply lower noise.

Newtonian noise

●Comparison of differences in Roughness height



(0.1Hz–10Hz: 900s–1000s
10Hz–100Hz: 1000s–1010s,)

・Integrate x=−6 m～6 m, y=−0.2 m～0.2 m area gravitation by water mass.

・0.1mm and 3.2mm were the noisiest conditions up to 10 Hz. The noise in the other conditions is approximately the same magnitude.

・3.2mm condition was noisier than 0.1mm condition up to 100 Hz.

・The reason the noise is louder under condition 0.1mm is thought to be the effect of the faster flow velocity due to the smoother surface. However, the reason why the noise is higher in condition 3.2mm is not yet known.

Summary of Newtonian noise

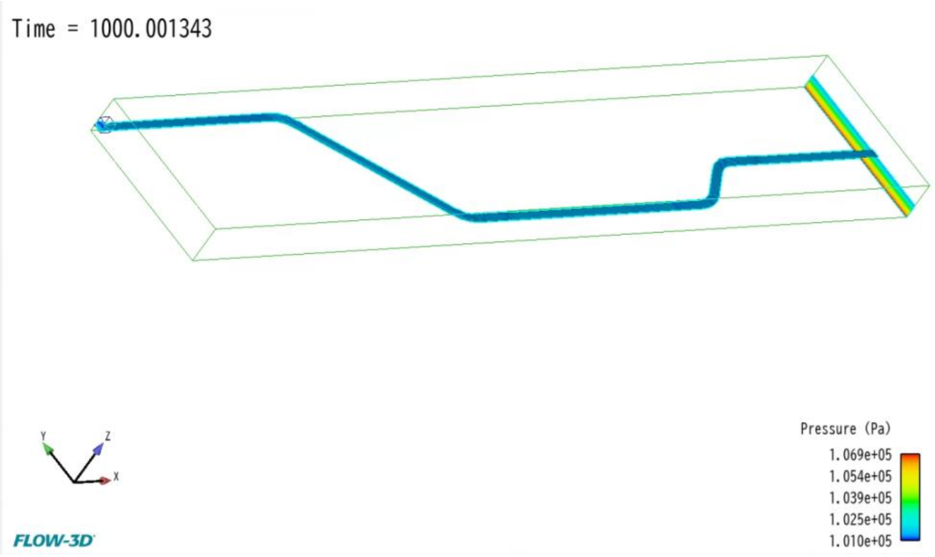
- In this setup (20 m straight pipe), the gravity gradient noise is sufficiently smaller than KAGRA's design sensitivity.
- However, the sensitivity of ET may be affected by Newtonian noise from water in the low frequency range. Therefore, there may be a need to move the waterway away from the test mass in ET.
- This condition is simple and calm, so it is possible to be large in real Y-end condition.
- Conditions of the highest water volume is the smallest noise.
- For Roughness height, the noise was the highest under the largest condition. However, even in the smallest condition, the noise is large below 10 Hz, so further analysis is needed.

Future work

- We will analyze in detail the causes of the differences in the intensity of the noise under different conditions.
- Simulate the real Y-end pipe (ex. curve, gradient, pipe length). We design pipes with the same geometry as real pipes to simulate water.
- Finally, compare the simulation result with the KAGRA data.

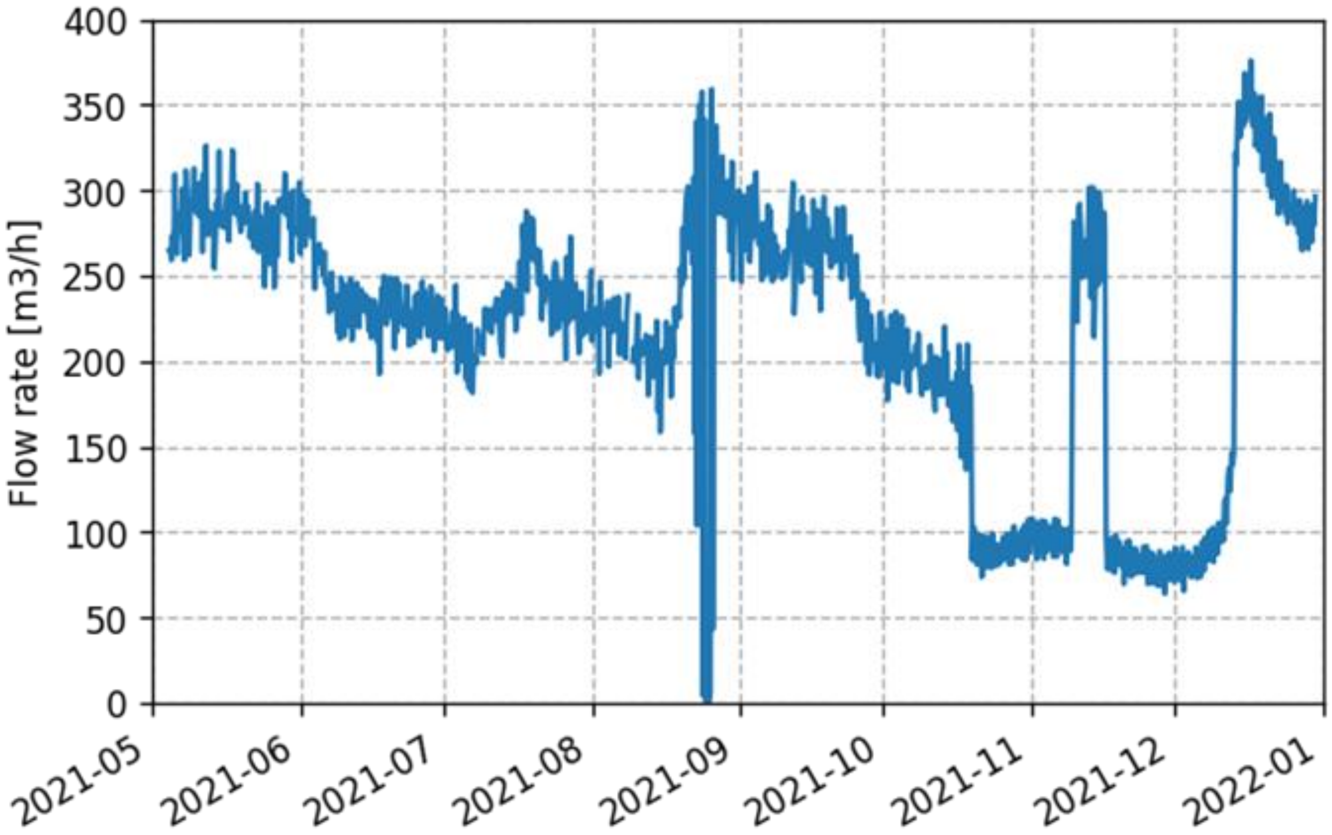
Future work(realistic pipe)

- We are designing a curved pipe of about 40 meters. This structure is as close as possible to the actual pipe.
- We believe that the values are close to those of actual Newtonian noise because they are close to the actual situation.

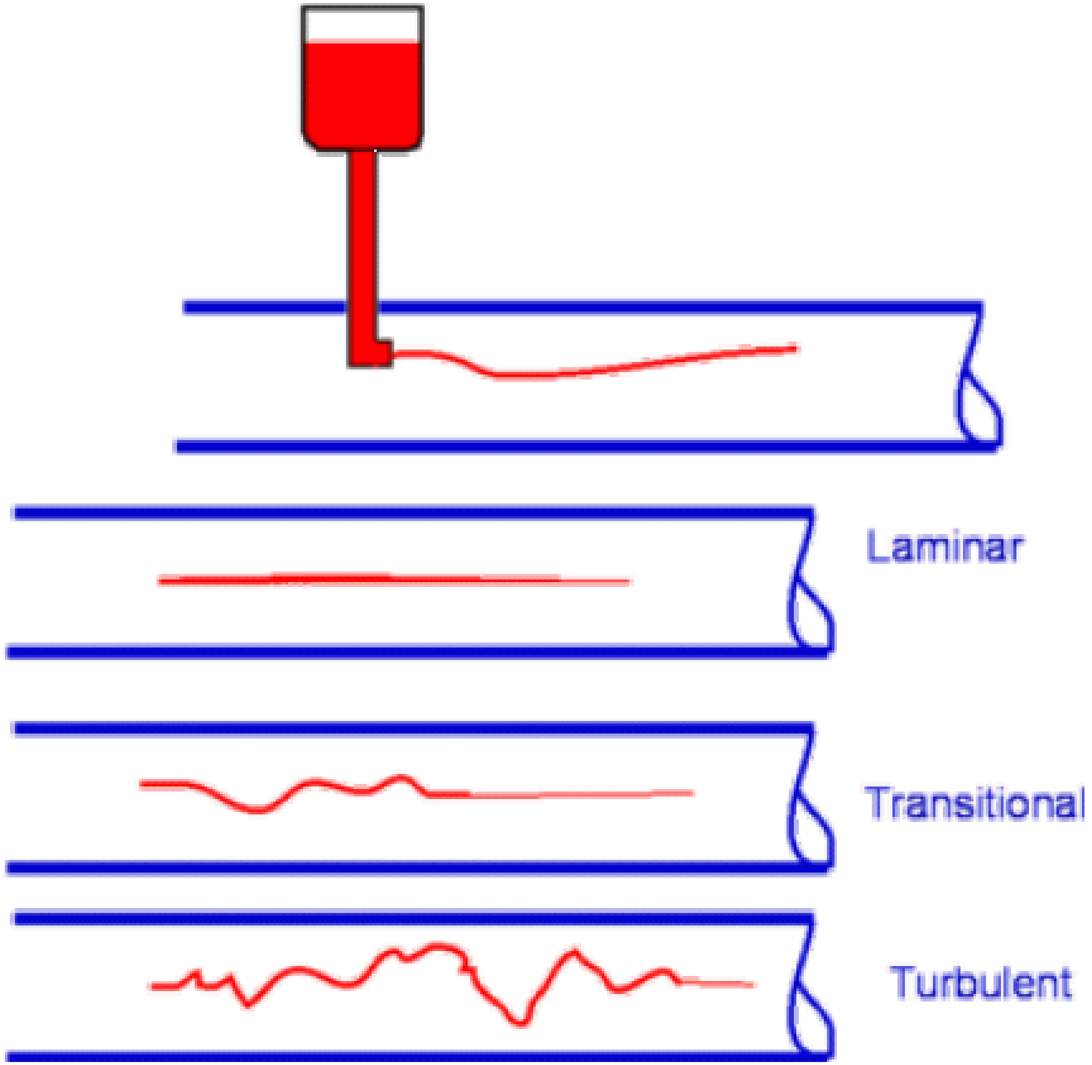


Appendix

Real flow rate



Turbulent flow, Laminar flow



Laminar is a straight flow
Turbulence makes the flow random