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EFFICIENCY OF CEMENT GROUTING ON THE TRIAXIAL RESPONSE OF BLOCK-SAMPLED LIQUEFIABLE SAND

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ABSTRACT

Soil liquefaction and associated ground failures have been a major source of damage during the past earthquakes. The risk of liquefaction and subsequent deformation can be reduced by various ground improvement methods including the cement grouting technique. In this paper, a large-scale experiment was developed for assessment of cement grouting effect on liquefaction potential and cyclic behavior of loose sand.
The large-scale test was made using Firouzkooh sand in a container of 1.2 m diameter and approximately 1.0 m height. The sand was compacted to a relative density equal to 25%. Then it was saturated, and loaded with a vertical pressure by means of air pressure and pressure plate. A perforated pipe was used to inject the micro-fine cement based grout in the sandy ground model. The test set-up allows measuring the efficiency of the grouting process and the drainage due to densification of the sand and bleeding of the grout. Four tests have been performed with equivalent sand densities, different grout properties and different loadings on the sand.
Cyclic triaxial tests were done on grouted sand samples at different distance from injection tube. The behavior of pure sand was compared with the behavior of sand grouted with a micro-fine cement grout. The effects of the grouting treatment, the distance from injection tube, the confining pressure and the cyclic stress ratio on cyclic behavior were studied. The test results were shown that cement grouting with low concentrations significantly decreased the liquefaction potential of loose sand and related ground deformation.

Keywords: liquefaction remediation; cement grouting; loose sand; large-scale experiment.

INTRODUCTION

Soil liquefaction and associated ground failure have been a major source of damage during many past earthquakes. In general terms, liquefaction refers to the loss of strength in saturated, cohesionless soils due to the build-up of pore pressures during dynamic loading. Liquefaction primarily occurs in geologically young sediments of sands and silts in areas with high ground water levels. Evidence of liquefaction has been prevalent in recent as well as in historic earthquakes. Sediments most susceptible to liquefaction include saturated Holocene to late Pleistocene age deposits, river channel and flood plain alluvium, Aeolian deposits, and poorly compacted fills.

During many large earthquakes, soil liquefaction results in ground failures in the form of sand boils, differential settlements, flow slides, lateral spreading, and loss of bearing capacity beneath buildings. Such ground failures have inflicted much damage to the built environment and caused significant loss of life.

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The risk of liquefaction and associated ground deformation can be reduced by various ground-improvement methods including densification, solidification (e.g., grouting). Grouting is also considered a highly reliable remedial measure against liquefaction. It prevents soil particle movement and provides cohesive strength. During the 1989 Loma Prieta earthquake, the few sites improved by grouting techniques performed well (Mitchell and Wentz, 1991; Graf, 1992).

The most widely used grouting techniques for mitigation of liquefaction and ground improvement, are permeation grouting, compaction grouting and jet grouting. Compaction grouting involves the use of low slump, mortar-type grout pumped under pressure to densify loose soils by displacement. Permeation grouting involves the injection of low viscosity liquid grout into the pore spaces of granular soils. The base material is typically sodium silicate or micro-fine cements where the D_{15} of the soil should be greater than 25 times D_{85} of the grout for permeation. With successful penetration and setting of the grout, a liquefiable soil with less that approximately 12 to 15 percent fine-grained fraction becomes a hardened mass. Jet grouting forms cylindrical or panel shapes of hardened soils to replace liquefiable, settlement sensitive, or permeable soils with soil-cement having strengths up to 2,500 psi.

In this paper, a large-scale experiment was developed for assessment of cement grouting effect on liquefaction potential and cyclic behavior of loose sand. The grouting method was permeation grouting and the grouting material used in this experiment was micro-fine cement. Four model tests have been performed with equivalent sand densities, loadings on the sand and different grout properties.

MATERIAL

The materials used were the same during the four experiments. Firouzkooh No.131 sand was used in all the performed model tests. It is artificially siliceous sand with very strong, angular grains and poorly graded. The index properties of Firouzkooh sand are presented in table 1. The cement grout was used in this research program is composed of water, micro-fine cement with particle size less than 40 μm and mean grain size of 6 μm (RHEOCEM® 650), and a superplasticizer (RHEOBUILD® 2000 SF) which role is to disperse the cement particle. According to product information, RHEOCEM® 650 is superfine Portland cement that used for rock and soil injection. This cement has higher strength and faster setting time than normal cements. Because of a small particle size, this cement has very well penetration into small cracks and fissures and gives a good sealing effect against ground water flow. A gradation curve of Firouzkooh No.131 sand, RHEOCEM® 650 and the gradation range of most liquefiable sand (Tsuchida 1970) are shown in Fig.1.

Table 1. Index properties for Firouzkooh No.131 Sand

USCS classification symbol	SP
D_{60} *(mm)*	0.56
D_{50} *(mm)*	0.50
D_{30} *(mm)*	0.41
D_{10} *(mm)*	0.32
Coefficient of uniformity, C_u	1.75
Coefficient of curvature, C_c	0.94
Specific gravity, G_s	2.65
Minimum index density *(kg/m³)*	1377
Minimum index void ratio, e_{min}	0.629
Maximum index density *(kg/m³)*	1626
Maximum index void ratio, e_{max}	0.924

$C_u = D_{60}/D_{10}$, $C_c=(D_{30})^2/(D_{10}\,D_{60})$ where D_{10} is the grain size that corresponds to 10% passing, D_{30} is the grain size that corresponds to 30% passing, D_{60} is the grain size that corresponds to 60% passing.

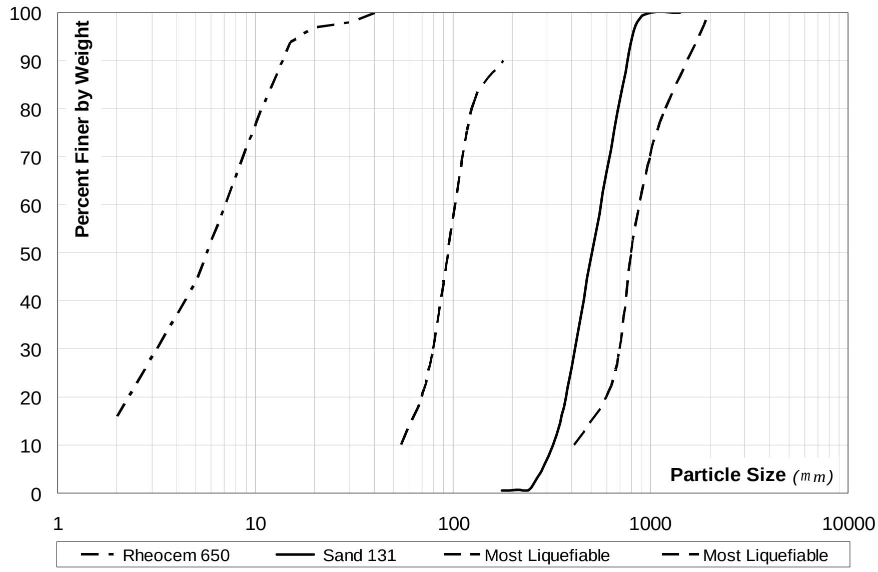

Figure 1. Grain size distribution for Firouzkooh No.131 sand and RHEOCEM® 650

EXPERIMENTAL PROCEDURES

Large-scale experiment

A three- dimensional cylindrical injection model was studied to examine the nature of pattern of grout flow for simulations similar to real grouting operations. The model cross- section is represented in Fig.2, including geometry, loading and instrumentation. The model was a cylindrical box with 1.20 m inside diameter and approximately 1.00 m length. A grout injection strainer pipe was positioned so that its axis should coincide with the axis of the model. The grout could be injected into the sand mass under constant pumping pressure or at pumping ratio. During the experiments a constant pumping rate was used.

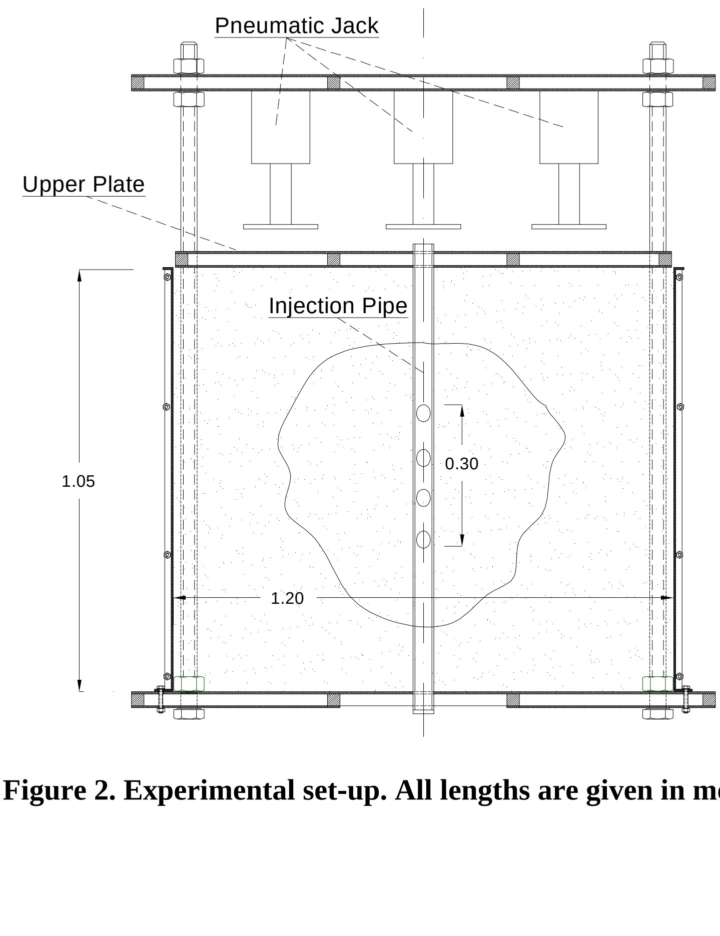

Figure 2. Experimental set-up. All lengths are given in meter.

The model was filled with Firouzkooh sand by moist tamping method to obtain reproducible models. The relative density of sand mass in four models was the same and equal to 25%. Due to the sand layers categorized as loose to very loose soils and strongly susceptible to liquefaction, this relative density was selected. The medium was saturated and its weight, initial porosity and density were measured before injection.

The grout was injected in the sand mass through 40 (6 mm inside diameter) holes evenly spaced along a finite length (0.3 m) of the injection pipe to simulate a continuous line source. Three water-cement ratio grouts (C/W=3, 6, 9) were injected in four models. A dispersant representing (1.5 percent of cement mass) certified an optimal stability and dispersed state of grout suspension. Fluidity and stability measurements were made over grout samplings during the experiments were shown that grout remained stable and can be treated as a homogeneous Newtonian solution during the propagation phase. Table 2 presents the injection parameters used in four experiments. The constant mechanical loading was uniformly distributed over the top of the models by pneumatics jack to simulate a ground depth of about 3.5 m during the four tests. The applied load was 5.0 ton/m^2 during the experiments.

Table 2. Injection parameters used in 4 models

	W/C	Grouting Pressure *(kPa)*	Pumping Rate *(l/min)*	Grout marsh cone *(Sec)*	Grout Vol. *(lit)*	Mechanical loading *(ton/m^2)*
Model 1	*3*	*50 ~ 150*	*3*	*9.77*	*120*	*5.0*
Model 2	*3*	*50 ~ 100*	*6*	*9.77*	*120*	*5.0*
Model 3	*6*	*50 ~ 150*	*6*	*9.2*	*120*	*5.0*
Model 4	*9*	*50 ~ 150*	*6*	*8.7*	*120*	*5.0*

Sampling

In each model tests, 24 h after grouting process, sampling of grouted sand was carried out at various depths and distances from grouting pipe. Thin-walled sampler was driven into grouted soil and consists of a thin-walled steel tube whose lower end is shaped to form a cutting edge with a small inside clearance. More than 15 undisturbed samples with 50 mm diameter and 110 mm length were obtained from each model tests.

Samples were placed in a moisture room for 28 days. Prior to testing, the top and bottom of each sample was levelled to meet the dimensional of the experimental apparatus (50 mm in diameter and 100 mm in length). A straight edge was used to trim the sample so that each sample had flat ends perpendicular to the longitudinal axis. The dimensions of the sample were measured and recorded.

Testing

The cyclic tests were run in general accordance with ASTM D5311 standard test method for load controlled cyclic triaxial strength of soil. Certain modifications to the test procedure were required because of the special properties of the treated sand. The pore pressure response and the axial strain during cyclic loading were measured to quantify the results of the treated soils. The confining stress used for all cyclic testing was 100 kPa. The equipment used for the cyclic triaxial testing was an automated triaxial testing system. The loading is controlled using closed-loop feedback systems capable of stress or strain controlled testing.

The UC strength was measured in general accordance with ASTM D2166 standard test method for unconfined compressive strength of cohesive soil and ASTM D4609 standard guide for evaluating effectiveness of chemicals for soil stabilization. UC test were done to investigate the distance and depth effects on strength behaviour of grouted sand. A strain rate of 1.5% per minute was used for all of the UC tests.

RESULTS AND DISCUSSION

In general, about 50 undisturbed samples were obtained from all model tests. Of these, 10 were tested cyclically and 20 were tested in UC. Additionally, UC tests were done on the samples after cyclic testing to determine the strength degradation due to cyclic loading.

Cyclic triaxial testing results

The success of the micro-fine cement grout treatment was evaluated by comparing the pore pressure response and the cyclic deformation resistance of treated and untreated samples. The deformation resistance of the treated sand was measured in terms of DA axial strain, which is the largest difference in strain that develops during an entire cycle of compression and extension. If the stabilized sands accumulate less strain during cyclic loading than untreated sands at a given CSR, then the treatment would be considered successful. The CSR is defined as the ratio of the maximum cyclic shear stress to the initial effective confining stress.

In general, samples stabilized with higher concentrations of micro-fine cement experienced less strain during cyclic loading than those stabilized with lower concentrations. When tested at a CSR of 0.50, samples with W/C=9 showed very little deformation during more than 500 cycles of loading. However, all samples remained intact during loading and were able to be tested for unconfined compressive strength after cyclic loading. The cyclic deformation behaviour of grouted sand with W/C=9 and CSR=0.50 is shown in Fig.3. Also the cyclic deformation behaviour of grouted sand with W/C=6 and W/C=3 and the same CSR are presented in Fig.4 and Fig.5.

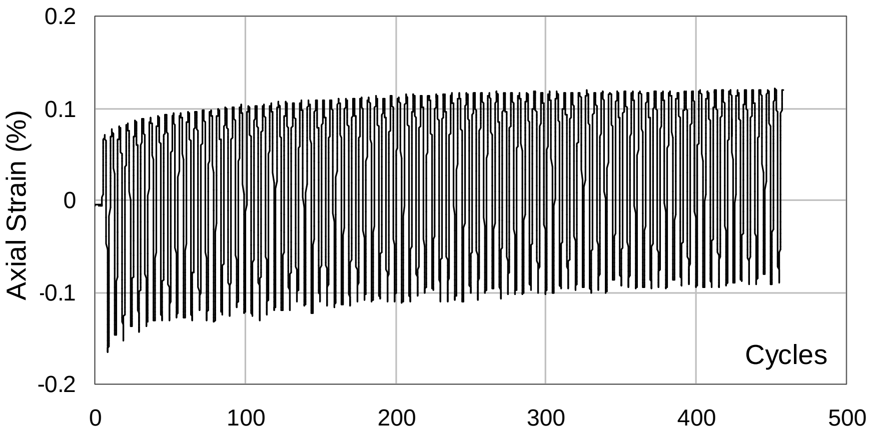

Figure 3. Axial Deformation during cyclic loading for treated sand (W/C= 9)

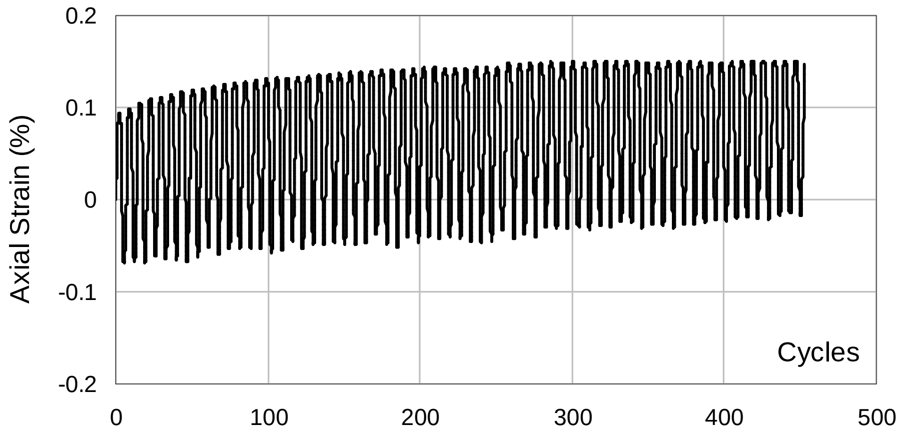

Figure 4. Axial Deformation during cyclic loading for treated sand (W/C= 6)

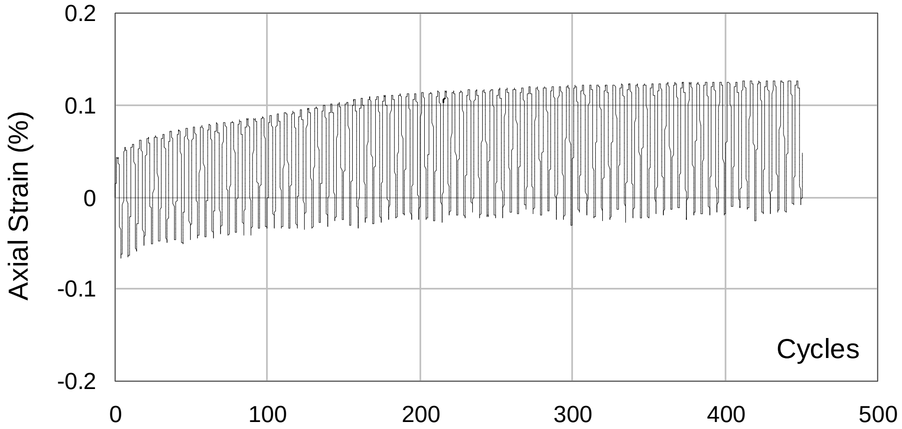

Figure 5. Axial Deformation during cyclic loading for treated sand (W/C= 3)

Distinctly different deformation properties were observed between grouted and ungrouted samples. Untreated samples developed very little axial strain prior to the onset of liquefaction. However, once liquefaction was triggered, large strains occurred rapidly and the samples collapsed within a few additional cycles. A cyclic resistance curve for loose Firouzkooh No. 131 sand at a relative density of 25% is shown in Fig.6.

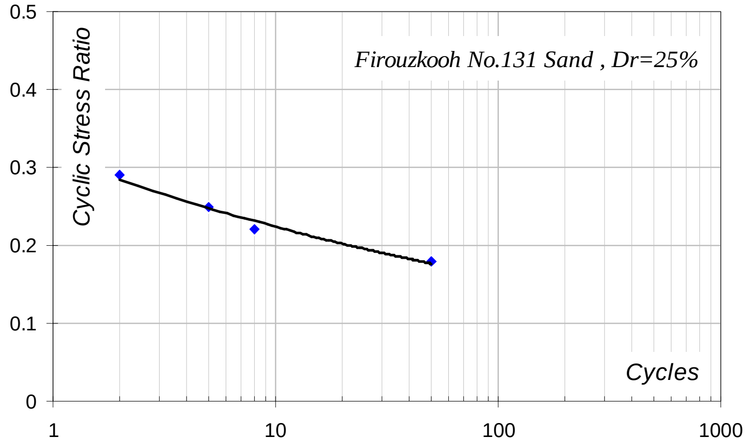

Figure 6. Cyclic resistance curve for loose sand

Unconfined compression test results

UC testing was selected to determine the static strength of treated sands because UC tests are often done on cement stabilized sands. They also have the advantage of being fast and easy. Baseline UC tests were done on samples not subjected to cyclic loading to determine the initial strength for samples treated with different distance and depth positions. After cyclic testing, UC tests were done on most of the samples to determine the residual strength for comparison with the baseline strength. The results of UC tests on treated sand with W/C= 3 and various distance from injection pipe are presented in fig.7. The UC strength of these samples ranged from 400 to 1100 kPa. Also for investigation the distance effect, UC tests were done on grouted samples and the UC behaviour curve of samples with W/C= 6 in different depth positions are shown in Fig.8.

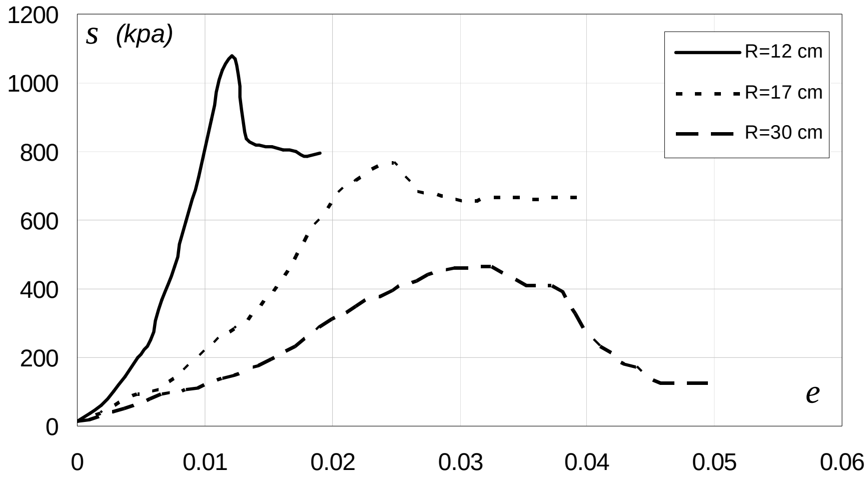

Figure 7. UC test result for treated sand W/C=3

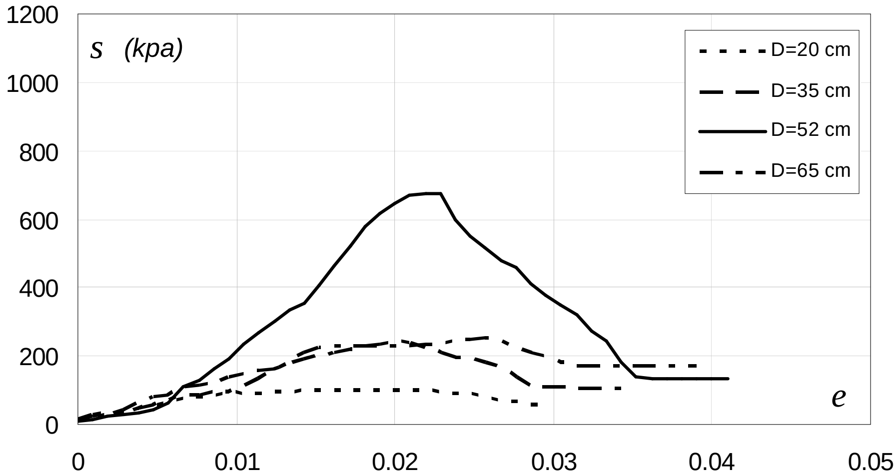

Figure 8. UC test result for treated sand W/C=6

Results was shown that UC strength of grouted sand decrease when distance from injection pipe was increased. Also in various depth positions, the UC strength was increased by depth increment, up to the medium level of model (D= 0.5 m).

CONCLUSION

Cyclic triaxial tests were performed to investigate the influence of micro-fine cement grout on the deformation properties and liquefaction resistance of loose sand. Overall, treatment with micro-fine cement grout with low concentrations significantly increases the deformation resistance of loose sand to cyclic loading. The following conclusions can be drawn.

1. In general, untreated samples experience much larger strains in fewer cycles than treated samples and collapse within one or two cycles of reaching 2% DA strain. In contrast, grouted sand samples experienced very little strain during cyclic loading. The strain that accumulated did so uniformly throughout loading and no treated samples collapsed.

2. Cyclic triaxial tests were done on samples stabilized with micro-fine cement at W/C between 3 and 9. Samples stabilized with W/C=9 showed less than 1.2% strain in 500 cycles of loading at a CSR of 0.50. Sands stabilized with lower W/C tolerated cyclic loading well and experienced less strain.

3. The baseline UC strength of grouted sand decrease when distance from injection pipe was increased. Also the UC strength was increased by depth increment, up to the medium level of model (D= 0.5 m) then reduced.

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