Prediction of jet grouting diameter in Swedish soil conditions

Mårten Brinck\textsuperscript{1}, Karl Stigenius\textsuperscript{2} and Anders Beijer Lundberg\textsuperscript{1,3}

\textsuperscript{1} ELU Konsult AB, Valhallavägen 117, Box 27006, 102 51 Stockholm, Sweden
\textsuperscript{2} Sweco Structures AB, Gjörwellsgatan 22, 112 60 Stockholm, Sweden
\textsuperscript{3} Corresponding author
E-mail: anders.beijer@elu.se

Abstract. Soil improvement by jet grouting has been used extensively in continental Europe and Japan, and its use has gradually increased in Scandinavia. The most frequent practical use of Jet Grouting in Sweden is water sealing of sheet pile wall excavations. In this application the diameter of the jet grouted columns governs the design, and the mechanical properties of the columns are of less importance. The existing methods for estimation of jet grouted column diameter have been developed in geological conditions in continental Europe and Japan, which are significantly different from the soil stratas normally encountered in Sweden. To assess the applicability of these methods for Jet Grouting in Swedish soil conditions, the current article provides a description of these methods as well as the Swedish geology in which jet grouting is commonly executed. The resulting predicted diameters from such methods are then examined for three different case studies in the Stockholm region in Eastern Sweden, and the design diameters of the columns are given. The applicability of the current methods is elaborated and the consequences for practical design is discussed. The work concludes that none of the two examined methods can be used by themselves in Swedish soil conditions but need to be supplemented with tests at site.

1. Introduction
Jet grouting is a ground improvement method which was originally invented in Japan, but its use has gradually spread around the world, and has been used in many different geological conditions, \cite{1}. Jet grouted columns are employed in construction for different purposes, e.g. retaining walls, water sealing, and for ground support, frequently presenting an economical alternative to other ground improvement methods, \cite{2}. Due to the peculiar geological conditions in Sweden, the jet grouting method is mainly used for water sealing in excavations, as an extension of the retaining walls. The most important parameter for jet column design for waterproofing is the column diameter \cite{3}: the low permeability of the completed column is typically sufficient, but cavities in the jet grouting columns significantly increase the waterflow into the excavation, \cite{2}.

In the design stage, the diameter is predicted, and during construction trial columns can be completed, or column diameter verification can be conducted, \cite{1}. Some different methods have been proposed, e.g. \cite{4} and \cite{5}. However, the uncertainty resulting from the variability of the jet column diameter is however significant and can either result in excessive waterflow into the excavation, or too conservative design. The aim of the design process is to reduce the construction risks while simultaneously providing an economical design.
Figure 1. A typical soil profile in Eastern Sweden. The cross sections 1 and 2 shows two different geological stratas considered for excavation design.

In the current paper, the prediction of jet grouting column diameter is explored in detail. Three case studies are introduced, and methods introduced in the scientific literature are used to assess and calculate the theoretical jet column diameter. This calculated diameter is subsequently compared to the diameter specified in the design, and in one case the measured diameter of the jet grouted columns. A description of typical Swedish geological conditions is also given in order to highlight that they differ from the regions where the methods for prediction originates, mainly Japan and the European continent where the soil strata frequently is dominated by fairly heterogeneous sandy soil layers.

2. Geological conditions in Sweden
The geological history of the Scandinavian peninsula has created a soil stratum dominated by the presence of both the very old bedrock and the very young soft soils. The bedrock consists of Precambrian crystalline rock, with a uniaxial compressive strength often in excess of 150-250 MPa. However, during the Weichsel era the area was covered with ice. All sedimentary layers was eroded and subsequently deposited as the inland ice receded. Glacial and postglacial clays consequently cover most of the urban areas, frequently with a high sulphide and organic content displaying a significant heterogeneity. These were deposited on layers of till, alternated with glacio-fluvial sands and gravel formed along glacial rivers underneath the ice cover.

Figure 1 shows an idealized soil profile in Eastern Sweden. The landscape is alternating between rock hills, sedimentary deposits and glacio-fluvial ridges expanding along the landscape. Naturally, urban development was initially developing along the areas presenting the most suitable building conditions: glacio-fluvial ridges and rock hills. However, most suitable areas have already been developed, especially in the vicinity of the capital Stockholm. Hence, most of the current urban development is taking place in the clay valleys. This has influenced the design of retaining walls and excavation in the country.

3. Retaining wall design and jet grouting in Sweden
3.1. Jet grouting and jet-soil interaction
In most soils jet grouting is possible. However depending of the soil different column properties can be accomplished and it requires for example different execution to accomplish the same diameter in different soils. In general regarding jet grouting, soils are divided into three groups, gravelly, sandy and clayey soils. The reason for this is that the jet grouting process works in different ways depending of the soil particle dimensions and interaction. Experiments have shown
that the formation of a jet grout column can be achieved by three different jet-soil interaction mechanisms, seepage, erosion and cutting [1]. The seepage effect is when the grout penetrates the empty space between soil particles and fills the cavities. The erosive effect is when the fluids flushes away existing soil particles and creates space for the grout to enter. Lastly the cutting effect is when the jets cut loose bigger soil parts and creates cavities for the grout to fill.

3.2. Retaining walls
Retaining walls are widely used to conduct excavations in urban areas. During construction, both the stability of the retaining walls and prevention of excessive water flow into the excavation are of importance. The latter factor can result in consequences both for the excavation work as well for the immediate environment. Groundwater control is therefore given much attention in design and execution of excavations.

Regarding the geological strata 1 in Figure 1, three different ground layers can be highlighted, with very different hydromechanical properties:

The soil glacial and post-glacial clay is almost completely impermeable during the time horizons of the normal construction project: hence no flow occurs in the clay layers. The flow will instead occur in the till layer, which has a highly variable permeability. The rock layer beneath the till is often fissured and can sometimes permit large waterflows.

The geological strata 2 is very different: The glacio-fluvial layers are highly permeable, preventing open excavations beneath the water table.

3.3. Jet grouting in retaining walls
Jet grouting can be included in excavations in both geological strata 1 and 2. In soil strata 1, jet grouted columns are executed between the sheet pile wall and the rock to seal the excavation. This is shown in Figure 2. The jet columns are produced fresh-in-fresh or fresh-hard, as shown in Figure 3.

The rock layer beneath the jet columns is frequently sealed with low-pressure grouting to clog the fissures in the rock and reduce the water flow.
Figure 4. Sealing of a sheet pile excavation with a jet grouted bottom plug.

In soil strata 2, a bottom plug is needed to seal the excavation. This is shown in Figure 4. After the completion of the sheet pile wall, a bottom plug is executed at the bottom of the sheet pile wall before excavation can start. The natural soil inside the sheet pile wall is therefore replaced with jet grout, resulting in both a mechanical stability as well as a water seal. This method is popular internationally and some design guidelines have been given, [9].

3.4. The reliability of excavation ground water sealing in soil strata 1 and 2
When the methods shown in Figure 2 and Figure 4 are used, the reliability of the water sealing of the retaining wall depends on the components of the system. Figure 5 shows the different components. During design and construction, excessive water flows are managed by adapting any of the components: Flow through the open sheet pile wall can be sealed with bitumen or any other sealant, and the rock layer is often considered impermeable after grouting. Most water flow is considered to occur through the jet grouted wall or bottom plug beneath the sheet pile wall. The design and execution of the jet grouted columns should therefore be done carefully to prevent excessive water flow into the excavation beneath the sheet pile walls. The diameter of the jet grouted columns is the most important parameter and should be predicted in the design process [3].

4. Proposed methods to predict the jet grouting diameter
Two different methods to predict the jet grouted column diameter $D_0$, are reviewed, Method 1 proposed in [10] and method 2 in [11]. Method 1 predicts the jet grouted column diameter through Equation 1 to 15. The input parameters are shown in Table 1 see [10], [11], [12], [13] and [14].

$$x_L = \frac{\Lambda \cdot d_0 \cdot v_0}{v_L}$$  \hspace{1cm} (1)

$$v_0 = \frac{4 \cdot Q}{M \cdot \pi \cdot d_0^2}$$  \hspace{1cm} (2)

$$\Lambda_g = \Lambda_w \cdot \sqrt{\frac{\mu_w}{\mu_g} \cdot \frac{\rho_g}{\rho_w}}$$  \hspace{1cm} (3)
\[ \rho_g = \frac{\rho_c \cdot (1 + \Omega)}{\Omega + \frac{\rho_w}{\rho_w}} \]  
(4)

\[ \mu_g = \frac{0.007}{\Omega^2} \]  
(5)

\[ \Lambda_{g,a} = \Lambda_g \cdot (1 + 0.054 \cdot \frac{p_a}{p_{atm}}) \]  
(6)

\[ v_L = \beta \cdot \left( \frac{q_a}{p_{atm}} \right)^k \]  
(7)

\[ \beta = b_0 \cdot \left( \frac{M_c}{100} \right)^{b_1} \cdot \left( \frac{D_{50}}{D_f} \right)^{b_2}, \quad 5 \leq M_c \leq 100 \]  
(8)

\[ \beta = b_0 \cdot \left( \frac{5}{100} \right)^{b_1} \cdot \left( \frac{D_{50}}{D_f} \right)^{b_2}, \quad 0 \leq M_c \leq 5 \]  
(9)

\[ q_u = 2 \cdot c_u \]  
(10)

\[ q_u = 2 \cdot (c' + \sigma' \cdot \tan \phi') \]  
(11)

\[ \eta = a_0 \cdot N^{a_2} \cdot \left( \frac{v_m}{v_m} \right)^{a_1} \]  
(12)

\[ v_m = \sqrt{(\pi \cdot R_s \cdot D_r)^2 + v_s^2} \]  
(13)

\[ N = M \cdot \Delta S_l \cdot \frac{R_s}{v_s} \]  
(14)

\[ D_0 = 2 \cdot \eta \cdot x_L + D_r \]  
(15)

In method 1 the calculation of the diameter relies on Equation 10 and 11, which makes it quite depth dependent. Even though field experiments [1] have shown that the effect of reduced column diameter due to high erosion resistance is relevant only for deep jet grouted columns and in soils with high friction angles, \( \phi' \geq 39^\circ \). Furthermore have field experiments shown that the most governing parameter for diameter variation is the soils homogeneity [15].

The second method, method 2, for prediction of \( D_0 \), is based on the concept of treatment Efficiency [1]. The mean diameter is calculated by Equation 16 and 17. The input parameter are shown in Table 2.

\[ D_0 = 1.128 \cdot \sqrt{p \cdot V_g \cdot \lambda_E} \]  
(16)

\[ \lambda_E = \frac{V_C}{V_g \cdot \gamma_g \cdot \left( \frac{\rho_w}{\rho_g} \right)} \]  
(17)

An alternative to Equation 17 is to use tables, for example as those presented in [1] to estimate, \( \lambda_E \), that contains typical values, obtained from field trials and experience for single fluid and double fluid systems in different soils, see Table 3.
### Table 1. Input parameters used in method 1, Equation 1 to 15

| Parameter                                                                 | Symbol | Unit  |
|---------------------------------------------------------------------------|--------|-------|
| Maximum erosion distance                                                  | $x_L$  | m     |
| Param. describing the int. between a grout jet and its surrounding fluid  | $\Lambda_g$ | -     |
| Param. describing the int. between grout and air                          | $\Lambda_{g,a}$ | -     |
| Param. describing the int. between a water jet and its surrounding fluid  | $\Lambda_w$ | -     |
| Diameter of the nozzle                                                    | $d_0$  | m     |
| Ejection velocity                                                         | $v_0$  | m/s   |
| Critical velocity                                                         | $v_L$  | m/s   |
| Flow rate of the fluid                                                    | $Q$    | m$^3$/s |
| Number of nozzles in the monitor                                          | $M$    | no.   |
| Dynamic viscosity of water and grout respectively                         | $\mu_w, \mu_g$ | Ns/m$^2$ |
| Density of water and cement respectively                                  | $\rho_w, \rho_c$ | kg/m$^3$ |
| Water-cement ratio                                                        | $\Omega$ | -     |
| Pressure of the injected air                                              | $p_a$  | kPa   |
| Atmospheric pressure                                                      | $p_{atm}$ | kPa   |
| Erosion resistance of the soil                                            | $q_u$  | kPa   |
| Characteristic velocity                                                   | $\beta$ | m/s   |
| Empirical constant                                                        | $k$    | -     |
| Content of fine particles smaller than 75 $\mu$m as a percentage          | $M_c$  | -     |
| Average size of soil particles                                            | $D_{50}$ | mm   |
| Size of the No. 200 sieve                                                 | $D_f$  | mm   |
| Effective cohesion                                                       | $c'$   | kPa   |
| Effective normal stress                                                   | $\sigma'$ | kPa |
| Effective friction angle                                                  | $\phi'$ | °     |
| Horizontal tangential velocity of the nozzle                              | $v_m$  | m/s   |
| Withdrawal rate                                                           | $v_s$  | m/s   |
| Rotation speed of the monitor                                             | $R_s$  | Rev/s |
| Diameter of the monitor                                                   | $D_r$  | mm   |
| Number of passes of the jet                                               | $N$    | no.   |
| Horizontal tangential velocity                                            | $v_{m0}$ | m/s   |
| Empirical parameters                                                      | $a_0, a_1, a_2$ | -   |
| Lift step                                                                 | $\Delta S_l$ | m     |
| Reduction coefficient                                                     | $\eta$ | -     |

### Table 2. Input parameters used in method 2, Equation 16 to 17

| Parameter                                                                 | Symbol | Unit           |
|---------------------------------------------------------------------------|--------|----------------|
| Energetic efficiency                                                      | $\lambda_E$ | -              |
| Injected volume of grout that remains in the column per unit length        | $V_g$  | m$^3$/m        |
| Total injected volume of grout per unit length                             | $V_c$  | m$^3$/m        |
| Unit weight of the grout                                                   | $\gamma_g$ | kN/m$^3$       |
| Outlet velocity                                                           | $v_0$  | m/s            |
| Ejection pressure                                                         | $P$    | MPa            |
Table 3. Typical values of $\lambda_E [m^3/MJ]$ [1].

| Soil type                        | Single fluid | Double fluid |
|----------------------------------|--------------|--------------|
| Sandy gravel                     | 0.067-0.100  | -            |
| From gravelly sand to silty sand | 0.033-0.067  | 0.077-0.125  |
| From sandy silt to clayey silt   | 0.020-0.033  | 0.077-0.025  |

Table 4. A compilation of the stratigraphy in the case studies. The soil type in bold is where the jet grouting columns are installed.

| Layer                          | Case 1       | Case 2              | Case 3               |
|--------------------------------|--------------|---------------------|----------------------|
| 1 Fill                         | Fill         | Fill                | Fill                 |
| 2 Clay                         | Sandy gravel | Sandy gravel        | Sandy gravelly till  |
| 3 Gravelly silty till          | (Bottom plug)| Sandy gravelly till |                      |
| 4 Bed rock                     | -            | Bed rock            |                      |

5. Case studies

5.1. Case study 1
In this case the jet grouting columns is utilized as a jet grouted wall extension, see Figure 2. The investigations performed at site shows a stratigraphy according to Table 4. The jet grouting is performed through pre-installed casing tubes. This is done to limit possible deviation of the position, angle and spacing to increase the quality of the jet grouting. The centre distance between the casing tubes is 0.6 m and the design diameter of each column is 1 m. The grouting is performed with the double fluid system using a grout pressure of about 40 MPa, a air pressure of about 0.2 MPa and a grout flow of about 300 l/min. The grout is mixed with a water cement ratio, $\Omega$, of 1.1. The rotation speed used, $R_s$, is 20 rpm and continuous lifting of 0.85 m/min is used. The jet grouting columns is roughly between 1 – 3 m and mostly performed fresh in fresh, see Figure 3. In this case no confirmation was performed that the design diameter of the columns was reached.

5.2. Case study 2
In this case the jet grouting columns is utilized as a jet grouted bottom plug, see Figure 4. The investigations performed at site shows a stratigraphy according to Table 4, which corresponds to strata 2 in Figure 1. In this case the design diameter of the columns is 1.5 m, the centre distance is 1.1 m and the spacing between the rows is 0.95 m. The single fluid system is used and the columns is performed as fresh in fresh sequence, see Figure 3, one row at a time. Furthermore a water cement ratio, $\Omega$, of 0.8 is used, with a grout pressure of 42 MPa and continuous lifting of 0.42 m/min with a rotation speed of 8 rpm. The length of the columns is circa 3 m. In this case the contractor were required to perform five test columns, with somewhat different treatment parameters, to validate that the overlapping was sufficient and that the design diameter was reached. This was done by visual inspection thus excavating to the top of the columns and measuring. By core drilling in the overlapping zone to determine its tightness, see Figure 6. Lastly by using hydrophones to confirm that the design diameter also is reached at the bottom of the columns.
5.3. Case study 3
In this case the jet grouting columns is utilized as a jet grouted wall extension, see Figure 2. The investigations performed at site shows a stratigraphy according to Table 4. During the production the authors acquired a soil sample of the friction soil and a sieve analysis was performed. The jet grouting is carried out using pre-drilling before jet grouting with a single fluid system. A grout pressure of about 42 MPa is used and a grout flow of about 265 l/min. The grout is mixed with water cement ratio, \( \Omega \), of 1.0 and intermittently lifting is used with steps of 4 cm with a stationary time of circa 7 s. The rotation speed, \( R_s \), is 15 rpm and most of the columns is between 1 – 4 m long. The design column diameter is 1.0 m with a centre distance of 0.6 m and the jet grouting is performed as fresh in hard, see Figure 3, with circa one day curing time before adjacent column is performed. In this case no confirmation was performed that the design diameter of the columns was reached.

6. Prediction of jet grouting column diameter for the case studies
In Table 5 the calculated diameters for each case is presented. The diameter is calculated for all cases using method 2 presented in section 4 and only for case 3 using method 1. The reason is that for method 1 proposed in [10] the average particle size is required something that was only possible to acquire for case 3 at the time of this study.

7. Discussion
The first method is somewhat more exhaustive, taking more parameters into consideration. The method needs for example two parameters evaluated from a sieve analysis, which is not common.

---

**Figure 6.** Core of the overlapping zone in case 2. Showing the overlapping zones tightness and how the soil has become the aggregate.

**Table 5.** Design and predicted diameters from the two different methods [m] [3].

|       | Design | Method 1 | Method 2 |
|-------|--------|----------|----------|
| Case 1 | 1.0    | -        | 1.0      |
| Case 2 | 1.5    | -        | 0.9      |
| Case 3 | 1.0    | 4.5      | 1.2      |
practice in Sweden. This was done in case 3 to be able to evaluate the method. Due to the quite large particles, as often the case in till, the method deems the soil easily erodible. Resulting in quite low \( v_L \) (Equation 7), i.e. velocity needed to cut through the soil, erode and transport the particles away. The resulting diameters in this soil gets unreasonably large and varies quite much with depth, which should not be the case according to tests performed by [1], as mentioned in section 4, when the friction angle lies below 39°. When evaluating the method it seems like it does not consider the possibility that particles can be of such size that they can not be eroded. This does not mean that it is impossible to perform jet grouting in such a soil but instead that the main jet-soil interaction mechanism has shifted from cutting and eroding to seepage. The method does therefore, in its current state, not seem to be applicable to till, one of the most common soil types in Sweden. To be able to use method 1 for till soil some adaption would need to be done.

The second method, method 2, is an easy way to make a fast estimation of the diameter. However the method is quite sensitive to some parameters. The first one is the ratio between the remaining grout and the total amount of grout. This is in most cases only an assumption, even during production this is hard to estimate. Since the spoil rising to the surface is a mixture of grout and soil flowing out onto the ground and often into pits. The volume may be possible to estimate if the spoil pits are carefully dug, but the issue with the soil-grout mixing still remains. The second parameter is \( \Lambda_E \), dependant on soil type and jet grouting system. Which system that is used is a quite easy task to conclude, however what soil type present at site might be a bigger issue. Even if there are naming rules, the names presented in Table 3 lumps together soil with quite varying properties and the values presented in the same table varies within quite large spans. This makes the method doubtful, suitable only for a estimation of the diameter early in the projects and needs to be complemented with validation methods prior to or during production. As it is a more basic method with fewer parameters, it was possible to use method 2 in all three case studies without doing any further soil investigations. The results are more promising than for the method proposed by [10], corresponding well to the design diameter for case 1 and case 3 but underestimating the diameter in case 2, see Table 5. This however makes it much harder to draw any conclusions about the method since the only project with confirmed diameter is case 2, the other two is only compared to their design values which might actually been used to back-calculate the parameters in the exact same way. One reason for the underestimation of the diameter in case 2 might be that the method does not account for some important parameters that can have a significant effect when constructing columns in sandy gravel. In such conditions seepage is an important jet-soil interaction mechanism and parameters such as rotation speed and lifting velocity influence the diameter quite much. This also becomes clear when looking at the logs from the monitoring systems in the different projects, where case 2 has far slower rotation and lifting velocities. In conclusion method 2 proposed by [1] would probably serve as a good first estimation of the column diameter but underestimates the diameter if jet grouting is performed correctly in esker material (soilstrata 2 Figure 1). This only proves once again that conformation of the column diameter is of great importance.

8. Conclusions
Throughout the work it has become clear that it is very hard to estimate the resulting diameter and it seems like there is no universal method or system to do such an assessment. It is also clear that the mean diameter has the most significant influence on the coverage and subsequently the sealing effect [3]. A conclusion that can be drawn is that as for most geotechnical solutions each jet grouting project is somewhat unique and that special care needs to be considered in the design and construction phase to ensure that the end product is adequate for its purpose. To do so, a suitable calculation method for the mean diameter can be chosen with the reasoning expressed in the Discussion part. This is still not the answer to the actual resulting diameter
and measurements and adjustments will probably need to be made during the execution until a confirmed diameter is established.

The calculation methods presented in section 4 for estimating the mean diameter, both show large dependence of soil type. For method 2, good correspondence is acquired with the design diameters in the till soils in case 1 and case 3 but not for the sandy gravel in case 2. With these results no actual conclusion can be drawn about its accuracy since none of case 1 or case 3 confirmed the resulting diameter. For method 1, the only calculated result is unreasonable and it is concluded that the method does not consider the influence of the larger particles in the till soil to a sufficient extent. From this we conclude that the confidence in both calculation methods is inadequate and further tests and investigations needs to be performed in common Swedish soils to raise the confidence for the methods as such and for jet grouting as sealing method when not confirming the diameter at site.

- None of the analytical or empirical methods that are evaluated to calculate the mean column diameter is reliable enough for Swedish soil conditions, the diameters need to be confirmed by testing at site.
- When designing and utilizing jet grouting for sealing sheet pile excavations in Sweden the most important things to consider to make it a viable option are;
  - That the design diameter of the columns is confirmed at site,
  - That the sealing capacity of the system is evaluated sometime during the process,
  - That casing tubes should be considered for large installation depths,
  - That special care should be put into measuring the inclination of the columns rather than their position [3],
  - And that an extensive control program is needed to minimize human errors.

References

[1] Croce P, Flora A and Modoni G 2017 Jet Grouting (Boca Raton: CRC Press, Taylor and Francis Group)
[2] Bell A L 1993 Ground improvement (Boca Raton: CRC Press, Taylor and Francis Group) pp 149–174
[3] Brinck M and Stigenius K 2019 Jet grouting as a method for sealing sheet pile excavations in Swedish conditions Master’s thesis KTH, Royal Institute of Technology
[4] Ochmański M, Modoni G and Bzówka J 2015 Soils and Foundations 55 425–36
[5] Wang Z F, Shen S L and Yang J 2012 Grouting and Deep Mixing 1 2044–51
[6] Gorbatschew R 1980 Geologiska Föreningen i Stockholm Förhandlingar 102 129–36
[7] Lundberg A B and Li Y 2015 Geotechnical Safety and Risk V (Amsterdam: IOS Press) pp 170–175
[8] Hall T 2008 Stockholm: the making of a metropolis 1st ed (London: Taylor & Francis)
[9] Modoni G, Flora A, Lirer S, Ochmanski M and Croce P 2016 J. of Geotech. and Geoenv. Eng. 142 04016018
[10] Shen S L, Wang Z F, Yang J and Ho C E 2013 J. of Geotech. and Geoenv. Eng. 139 2060–69
[11] Modoni G, Croce P and Mongiovi L 2006 Géotechnique 56 335–47
[12] Raffle J F and Greenwood D A 1961 5th Int. Conf. on Soil Mech. and Found. Eng. vol 2 pp 789–93
[13] Dabbagh A A, Gonzalez A S and Pena A S 2002 Soils and Foundations 42 1–13
[14] Yoshida H, Asano R, Kubo H, Jinbo S and Uesawa S 1991 6th American Water Jet Conf. pp 381–92
[15] Modoni G and Bzowka J 2012 J. of Geotech. and Geoenv. Eng. 138 1442–54